The Neurocognitive Basis of Age-Related Changes in Audiovisual Integration: Implications for Speech Perception and Fall Risk

Jessica Laura Pepper

Department of Psychology

Lancaster University

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Declaration

I declare that the work presented in this thesis is, to the best of my knowledge and belief, original and my own work. The material has not been submitted, either in whole or in part, for a degree at this, or any other university. For transparency, research from my MSc provided pilot work for Chapter 3, but this Chapter 3 bears no resemblance to the MSc thesis and is original. This thesis does not exceed the maximum permitted word length of 80,000 words including tables, figures, and footnotes, but excluding the thesis abstract, bibliography, and appendices.

Name: Jessica Laura Pepper

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Abstract

Multisensory integration is essential for the accurate perception of, and safe navigation through, our noisy, dynamic everyday environment. Evidence suggests that older adults exhibit increased, less accurate multisensory integration compared to younger adults, which can have a negative impact on activities of daily living such as speech perception and balance maintenance; the relationships between each of these concepts are explored in detail in Chapter 2. A greater understanding of the age-related changes in the bottom-up and top-down mechanisms of multisensory integration is key given our increasingly ageing population. As a result, Chapters 3-4 investigated the interplay between temporal precision and attentional control during audiovisual integration; the findings of these chapters suggested that the increased integration experienced by older adults could be attributed to weaker top-down attentional control and less modulated multisensory processing.

The most comprehensive account of how multisensory processing changes with healthy ageing may therefore come from investigating the neural correlates of attentional control; Chapters 4-6 explore the functional role of alpha activity (8-12Hz) in the inhibition of task-irrelevant information, and whether reduced alpha activity in older adults could reflect their weaker attentional control during audiovisual and auditory processing. These chapters produced novel insights as to how patterns of alpha activity may change as a function of healthy ageing. Potential reasons for this are posited throughout; a recurring theme was the impact of heterogenous ageing trajectories on an older adult's ability to employ compensatory strategies, to preserve speech perception and balance performance.

Taken together, this thesis has uncovered how age-related changes in the attentional modulation of sensory information may be reflected in alpha activity, and the impact of such changes on older adults' everyday speech perception and balance ability. The potential implications of this and directions for future research are discussed.

1. Introduction

1.1. Mechanisms of Multisensory Integration

1.1.1. What is multisensory integration?

The quick and accurate perception of our multisensory environment is contingent upon the integration of relevant, reliable sensory inputs and the suppression of irrelevant, noisy inputs, to form a unitary representation of the world around us (Stevenson et al., 2018; Talsma et al., 2010). Multisensory integration has been found to bring a variety of behavioural benefits, such as improved detection, improved localisation, and faster response times (Cornelio et al., 2021). This binding of visual and auditory sensory information is a complex process that requires both bottom-up and top-down mechanisms. For example, on a perceptual level, bimodal sensory inputs being presented closely together in space and time increases the likelihood of them being perceived as occurring from the same event, and subsequently being integrated (Calvert et al., 2004; Spence, 2007). In addition, on a cognitive level, this influx of sensory information must be modulated, for example by determining whether the two inputs are semantically congruent (Laurienti et al., 2004; Spence, 2007), or by allocating attentional resources to attending to relevant stimuli and suppressing irrelevant stimuli (Mozolic et al., 2008; Talsma et al., 2010). The contributions of each bottom-up and top-down mechanism in building an accurate representation of our complex, dynamic environment have been a topic of much debate over the last decade, especially with regards to how multisensory integration changes across the lifespan (Jones & Noppeney, 2021; Murray et al., 2016).

1.1.2. Multisensory integration in healthy ageing

Older adults are believed to exhibit increased multisensory integration compared to younger adults, showing faster response times and greater accuracy in response to multisensory stimuli than unisensory stimuli, compared to the responses of younger adults (Laurienti et al., 2006; Laurienti et al., 2004; Peiffer et al., 2007). At first glance, this seems beneficial – for example, being able to effectively utilise visual and auditory cues has been found to improve driving performance in older adults (Ramkhalawansingh et al., 2016). As a result, previous literature has framed integration in older adults as "multisensory benefits" or "enhanced integration" (Laurienti et al., 2006). However, it is important to note that these "benefits" are simply describing the improved speed and accuracy older adults exhibit in response to bimodal stimuli compared to unisensory stimuli. Instead, when considering the key perceptual and cognitive mechanisms of multisensory integration that appear to deteriorate with healthy ageing, the picture is much more negative, with older adults experiencing increased integration of task-irrelevant stimuli and integration that is less temporally precise. As a result, it could be argued that the use of the phrase "multisensory benefits" when describing the differences in multisensory integration between younger and older adults may be misleading in this context. Instead, when describing "increased integration", it is the less accurate, less modulated multisensory integration of older adults that is being referred to.

Indeed, previous research suggests that increased integration can be detrimental to veridical perception, due to the fact that older adults may be more prone to integrating sensory inputs that are incongruent, task-irrelevant, or not temporally aligned (Bedard & Barnett-Cowan, 2015; Hirst et al., 2019; Setti et al., 2014; Jones & Noppeney, 2021). Age-related changes in both bottom-up mechanisms such as temporal processing, and top-down mechanisms such as attentional control, have been postulated as key factors in increased integration older adults (Mozolic et al., 2012; Bedard & Barnett-Cowan, 2016). This marked an important shift in multisensory research, highlighting the importance of acknowledging both perceptual (stimulus-driven) factors and cognitive factors in multisensory integration (Talsma et al., 2010). Due to the importance of multisensory integration in building an accurate representation of our environment, the increased, erroneous integration experienced by older adults can often be dangerous, and can have a negative impact on their performance in activities of daily living, such as speech perception and balance maintenance (de Dieuleveult et al., 2017; Setti et al., 2011; Setti et al., 2014). Given our increasingly ageing population, it is of utmost importance that a detailed understanding of age-related changes in multisensory integration is developed, including how such changes are reflected in the brain, and the impact that they have on an older adult's quality of life.

This thesis consists of a series of investigations into the perceptual and cognitive mechanisms involved in audiovisual processing, and how these are affected by increasing age. A particular emphasis will be placed on understanding the neural correlates of attentional control during audiovisual integration, analysing differences in oscillatory neural activity between younger and older adults. In addition, throughout each project, the importance and real-world relevance of investigating the age-related changes in multisensory integration will be discussed, specifically with regards to the impact that such changes have on the everyday life of older adults during tasks like speech perception and balance maintenance.

1.1.3. Bottom-up mechanisms of multisensory integration: Temporal processing

The key perceptual characteristics that influence the likelihood of visual and auditory inputs being bound together are their spatial and temporal proximity (Vroomen & Keetels, 2010). From a bottom-up perspective, some researchers have focussed on studying the differences between younger and older adults in the temporal processing of auditory and visual stimuli (Setti et al., 2011; Bedard & Barnett-Cowan, 2016; Baum & Stevenson, 2017; Stevenson et al., 2018). If bimodal inputs are presented closely together in time, they are more likely to be perceived as occurring from the same event and bound together into a single perceptual entity (Meredith & Stein, 1985; Bedard & Barnett-Cowan, 2016). This is known as the "temporal rule" of multisensory integration. The time frame within which two sensory signals from different modalities can be presented, processed and integrated is referred to as the temporal binding window (TBW). A common way to measure the TBW in the laboratory often involves asking participants to complete simultaneity judgement tasks (deciding whether two different sensory inputs were presented at the same time or at different times), or completing temporal order judgement tasks (deciding which of the sensory inputs occurred first; Bedard & Barnett-Cowan, 2016). A narrower TBW facilitates more precise temporal processing, and therefore in theory, having a shorter time frame over which integration can occur should produce a more accurate multisensory percept.

With increasing age, the TBW becomes wider, to the extent that older adults may erroneously bind together visual and auditory inputs that do not occur at the same time and therefore should remain separate (Bedard & Barnett-Cowan, 2016; Mozolic et al., 2012). For example, Chan et al. (2014) presented auditory and visual sensory inputs to younger and older participants, and found that older adults required a larger stimulus-onset asynchrony (SOA) for the two inputs to be perceived as occurring at different times. The researchers concluded that this was indicative of older adults having a wider temporal binding window than younger adults (Chan et al., 2014; Bedard & Barnett-Cowan, 2016). The wider temporal binding window of older adults can result in noisy, confusing perceptions of their dynamic environment, supported by the fact that the wider TBW of older adults is also associated with their increased risk of falls (Mahoney et al., 2014; Setti et al., 2011; see section *1.3.1*). Multiple researchers have postulated potential reasons for the weaker temporal precision in older adults during multisensory integration. For example, age-related decreases in GABA as an inhibitory neurotransmitter could reduce an older adults' ability to inhibit noisy or irrelevant sensory inputs, which may lead to an increased difficulty in recognising the temporal order of incoming bimodal sensory signals (Caspary et al., 2005; Bedard & Barnett-Cowan, 2016). Nevertheless, it remains clear that the wider TBW of older adults is problematic for veridical perception due to the increased integration of bimodal sensory inputs that may not be occurring closely together in time.

1.1.4. Bottom-up mechanisms of multisensory integration: Spatial location

In order for two sensory inputs to be perceived as occurring from the same event, another key perceptual characteristic is that they originate from similar locations in space. This is known as the "spatial rule", which argues that multisensory integration is dependent upon the proximity with which stimuli from two different modalities are presented (Spence, 2013).

In neural terms, this would mean that bimodal stimuli have an increased likelihood of being integrated if they stimulate cells that have overlapping receptive fields in the superior colliculus, producing a neural response enhancement (Spence, 2013; Meredith & Stein, 1996; see section 1.2). With regards to audiovisual integration, the spatial rule has been measured most frequently using the ventriloquist effect (Bruns, 2019; Chen & Vroomen, 2013). For example, presenting a sound at the same time that a light is presented at a different location shifts the perceived location of the sound towards the visual stimulus.

In contrast to the temporal processing required in multisensory integration, spatial localisation appears to be generally preserved with healthy ageing (Jones et al., 2019; however, see Park et al., 2021). That is, despite older adults generally producing a slower performance, they show a similar tendency as younger adults to integrate visual and auditory stimuli that is spatially proximal (Jones et al., 2019; Stawicki et al., 2019). Indeed, any differences in multisensory integration that have previously been detected between younger and older adults in renowned audiovisual tasks like the sound-induced flash illusion (Chan et al., 2014; Setti et al., 2011; DeLoss et al., 2013; McGovern et al., 2014) are more likely to be attributed to age-related changes in temporal precision as opposed to spatial localisation. As such, whilst both the temporal rule and the spatial rule are important features of bottom-up sensory processing, there is more evidence to suggest that age-related changes in temporal precision have the greatest influence on the increased multisensory integration exhibited by older adults. It is therefore reasonable to explore whether certain higher-level, top-down mechanisms could modulate, or improve, the temporal precision of sensory processing, to allow older adults to produce a more accurate multisensory percept.

1.1.5. Top-down mechanisms of multisensory integration: Attentional control

One potential top-down mechanism involved in the modulation of audiovisual integration is attentional control. When multiple sensory modalities are receiving lots of competing inputs (therefore the salience of each discrete input is low), top-down selective attention is essential for identifying and integrating congruent stimuli, and for the inhibition of task-irrelevant or incongruent stimuli (Talsma et al., 2010; Talsma et al., 2007; Mozolic et al., 2008; Posner & Driver, 1992). This top-down directed attention can therefore modulate audiovisual processing – if the multimodal inputs are congruent, multisensory integration is facilitated (i.e. more accurate responses, faster response times), however if the inputs are incongruent, inhibitory control is required to prevent them from being integrated (Fairhall & Macaluso, 2010). As a result, if inhibitory control fails, this would lead to interference with audiovisual integration (i.e. decreased accuracy, slower response times; Talsma et al., 2010) and produces an unstable, inaccurate percept of the environment.

A key facet of selective attention is the ability to inhibit the processing of sensory information that is irrelevant to the task at hand (Hasher et al., 1999; Hasher & Zacks, 1988; Borghini et al., 2018). In everyday life, we are bombarded with a massive amount of visual and auditory information; to avoid overwhelming our cognitive and perceptual systems, strong inhibitory mechanisms are required to filter out irrelevant information to prevent it from being processed further and integrated with other sensory inputs (Klatt et al., 2020). Lustig et al. (2007) summarised the functions of inhibition as "a) controlling access to attention's focus, b) deleting irrelevant information from attention and working memory and c) suppressing strong but inappropriate responses". With regards to the access element of this framework, "inhibition serves to prevent irrelevant information from gaining access to the focus of attention" (Lustig et al., 2007) – that is, access control reduces the influence of distractors when processing target stimuli. If access control fails, then distracting or irrelevant sensory information is processed, and the deletion function of inhibition then serves to recognise this information as irrelevant to the current task and remove it from the focus of attention (Lustig et al., 2007). This sequential, top-down modulation of sensory information involves a network of multiple different "control" regions in the brain, including the prefrontal cortex and the parietal cortex (Curtis & D'Esposito, 2003; Gazzaley & Nobre, 2012). This thesis predominantly focuses on investigating the role of top-down attentional mechanisms in the modulation of multisensory integration, and how age-related changes in attentional control may be an intrinsic factor in the increased integration exhibited by older adults.

1.1.6. Age-related changes in attentional control

Previous research suggests that older adults find it more difficult to inhibit irrelevant sensory information compared to younger adults – this is known as the inhibitory deficit hypothesis (Hasher & Zacks, 1988). According to the inhibitory deficit hypothesis, older adults may find it more difficult to engage their attentional mechanisms to inhibit task-irrelevant, distracting sensory inputs; these difficulties can have a negative impact on task performance due to disproportionate interference effects relative to younger adults (Guerreiro et al., 2010; Lustig

& Hasher, 2001). If task-irrelevant, distracting information fails to be suppressed and is instead incorporated into the multisensory percept, this can result in older adults' producing a less accurate representation of their environment. Furthermore, it is important to not only explore age-related changes in attentional control in isolation, but also to consider how these changes interact with bottom-up temporal processing. Indeed, some researchers have postulated that strong attentional control mechanisms can narrow with width of the TBW, sharpening temporal precision to enhance perceptual performance (Donohue et al., 2015; Powers et al., 2012). The weaker attentional control of older adults may mean that the boundaries of the TBW are therefore less restricted; the subsequent greater time range over which integration can occur could result in older adults experiencing increased multisensory integration and a less accurate representation of the environment (Pepper et al, 2023; Brooks et al., 2018; Setti et al., 2011).

Crucially, previous research suggests that these age-related changes in attentional control can have a significant impact on an older adults' performance on a wide range of multisensory tasks in everyday life. Namely, if older adults are more distractible due to the increased integration of task-irrelevant information, this has been linked to increased fall risk (Setti et al., 2011). Furthermore, in everyday conversational environments, background noise must be suppressed to facilitate the processing of target speech – age-related attentional deficits may be a significant contributor to the common difficulties that older adults have in perceiving speech in noisy listening environments (Wostmann et al., 2015; Pichora-Fuller et al., 2017). Taken together, it is clear that a more detailed understanding is required of the age-related changes in the attentional mechanisms involved in multisensory integration, and the impact that this can have on older adults' perceptual performance. Analysing the neural correlates of such mechanisms can provide key insights into how the top-down modulation of multisensory integration may change as a function of healthy ageing.

1.2. Neuroscience of Multisensory Integration

1.2.1. Neuroanatomy of multisensory integration

Due to the fact that, by definition, multisensory integration involves one sensory modality affecting the neural activity produced by another sensory modality (de Dieuleveult et al., 2017), a large amount of research has focused on pinpointing the key brain areas responsible for binding congruent sensory inputs together. Two key brain areas have been regularly identified – the superior temporal sulcus (STS) and the superior colliculus (SC). The position of the STS, between the visual association cortex and the posterior temporal region, is a clear target for research into audiovisual integration, serving as a convergence area for the sensory inputs processed by the visual system and the auditory system to form a unified percept (Venezia et al., 2017; Wallace & Stevenson, 2014; Beauchamp et al., 2010; Beauchamp et al., 2005; Stevenson & James, 2009). A key finding that supports the role of the STS in audiovisual integration is its reflection of the super-additivity theory of multisensory processing, in that exposure to stimuli from two different modalities elicit a greater neural response in the STS than exposure to unimodal stimuli (Beauchamp et al., 2005). For example, whilst the posterior STS shows increased activation in response to visual stimuli, and the anterior STS shows increased activation in response to auditory stimuli, the greatest activation across the STS is evoked from exposure to audiovisual stimuli (Wright et al., 2003). The STS has been specifically implicated in the evaluation of the temporal factors associated with multisensory integration, such as the temporal binding window. For example, Calvert et al. (2000) found that when contextually and temporally congruent visual and auditory information was presented to participants, the STS displayed greater neural activity than when the visual and auditory information was incongruent.

The evaluation of the spatial and temporal proximity of multimodal stimuli has also been identified as a key role of the superior colliculus (SC). Given its location in the midbrain, the SC has proven to be difficult to study in humans, therefore the majority of the research into its role in multisensory integration has been based on single neuron studies in cats (Stanford et al., 2005; Rowland et al., 2007; Wallace & Stein, 1997). The key finding of these studies is that stronger neural activity in the SC is evoked in response to multisensory inputs that are spatially and temporally proximal, compared to the activity evoked when unisensory inputs are presented (Meredith et al., 1987; Holmes & Spence, 2005). Crucially, not only does the SC have projections to visual, auditory and somatosensory cortices (Meredith et al., 1992), but evidence also suggests that the SC can interact with higher-level cortical brain regions involved in attentional networks (Talsma & Woldorff, 2005); this may highlight the SC as a key brain region involved in the interplay between bottom-up and top-down mechanisms in multisensory integration. For example, reciprocal connections between the SC and the parietal cortex have been implicated in coordinating attention across modalities and orienting attention towards target stimuli (Talsma & Woldorff, 2005; LaBerge, 1995; Stein & Meredith, 1993). Taken together, the STS and the SC have served as the predominant focal points for research into the neurobiology of multisensory integration, identifying how subcortical and cortical brain regions may interact during the top-down modulation of sensory processing.

1.2.2. Neural oscillations – the functional role of alpha activity

Whilst the investigation of these key brain areas has significantly developed our understanding of multisensory integration, important insights can also be uncovered from analysing oscillatory neural activity, particularly with regards the to the functional role of different cortical activations during perceptual and cognitive processes. Neural oscillations refer to patterns of neural activation arising from the synchronised firing of neurons. Oscillations are classified into different frequency bands – delta (3-4Hz), theta (5-8Hz), alpha (8-12Hz), beta (13-30Hz) and gamma (>30Hz; Keil & Senkowski, 2018). Previous research suggests that each frequency band is associated with different functions – broadly speaking, gamma activity is believed to index bottom-up sensory processing, beta activity is associated with predictive coding and motor control, and crucially, alpha activity has been studied in relation to attentional control and inhibition (Keil & Senkowski, 2018).

From a stimulus-driven perspective, previous research has found that increased gamma-band activity is associated with low-level perceptual binding of the visual and auditory stimuli (Keil & Senkowski, 2018). For example, increased gamma activity has been found to be correlated with an increased susceptibility to the SIFI, and the related touch-induced flash illusion (Mishra et al., 2007; Lange et al., 2011; Bhattacharya et al., 2002), especially within in the superior temporal gyrus (Balz et al., 2016). If gamma activity reflects the low-level, bottom-up processing of sensory stimuli, this raises the question of which frequency band is responsible for moderating this influx of sensory information. Alpha activity (8Hz-12Hz) has been regularly implicated in the attentional modulation of multisensory integration. For the purposes of analysing how it changes as a function of healthy ageing, alpha activity can be explored in relation to the "gating-by-inhibition hypothesis". This hypothesis suggests that alpha activity is an inhibitory mechanism which suppresses task-irrelevant information, in order to increase availability of cortical resources for relevant information (Jensen & Mazaheri, 2010). At this point, it is important to note that an inverse relationship exists between alpha power and brain activity – lower alpha power is associated with greater neural activation, whilst higher alpha is associated with less neural activation (Shaw et al., 2018). Crucially, an increase in alpha power is believed to reflect the ability to ignore task-irrelevant information, whilst decreases in alpha power may reflect an increased activation of engaged brain regions to facilitate attention towards the target stimuli (Wostmann et al., 2017; Jensen & Mazaheri, 2010). Due to the central role of attention and inhibition in the top-down modulation of multisensory integration, the studies in this thesis focussed on measuring and entraining alpha activity, and investigating how age-related changes in alpha activity may underlie the increased audiovisual integration exhibited by older adults.

This functional inhibition by alpha activity is believed to be associated with optimal task performance (Jensen & Mazaheri, 2010). In situations when task-irrelevant sensory information must be inhibited, alpha power must increase to suppress the processing of these inputs and reduce the likelihood of them being integrated into the multisensory percept. Furthermore, in situations when the stimuli is congruent and should be bound together, alpha power must decrease in order to facilitate the processing of these inputs in higher-level brain regions. For example, O'Sullivan et al. (2019) presented participants with congruent or incongruent auditory and visual speech inputs, under clear or noisy listening conditions. The researchers found that when inputs were incongruent and therefore should not be integrated, parieto-occipital alpha power increased to suppress the irrelevant visual information. The reduced influence of distracting visual inputs facilitated the processing of the target auditory signal. Likewise, when the visual and auditory information was congruent, alpha power decreased to facilitate audiovisual integration and improve the speed and accuracy of speech perception (O'Sullivan et al., 2019; Pepper & Nuttall, 2023).

From this, and based on the theories discussed regarding the weaker attentional control exhibited by older adults compared to younger adults, it would be fair to suggest that each age group may display different patterns of alpha activity during audiovisual processing. For example, after implementing a working memory task, Borghini et al. (2018) found that older adults displayed weaker inhibition of distracting visual information compared to younger adults, which was reflected in older adults having lower alpha activity. Likewise, it is well-established that older adults have weaker speech-in-noise perception compared to younger adults (Slade et al., 2020; Pichora-Fuller et al., 2017; Getzmann et al., 2016), exhibiting a reduced ability to inhibit the task-irrelevant background noise in their environment. Wostmann et al. (2015) found reduced overall alpha power in older adults during challenging listening conditions, attributing this to the decreased maintenance of selective attention and less efficient inhibition of task-irrelevant information in older adults compared to younger adults (Wostmann et al., 2015; Sander et al., 2012). However, many paradigms in this area involve exposing younger and older adults to unisensory information, therefore limited evidence exists as to how age-related changes in audiovisual integration may be reflected in alpha power.

Taken together, it is clear that analysing oscillatory alpha activity during audiovisual processing can provide key insights into how the top-down modulation of integration may change as a function of healthy ageing. Above all, it is important to measure the impact that these age-related changes can have on performance in everyday multisensory tasks like balance maintenance and speech perception, in which attention must be allocated to the most relevant sensory inputs and distracting background information must be inhibited.

1.3. Age-Related Changes in Multisensory Integration: Real-world Implications

1.3.1. Real-world implications: balance ability

It is well-established in previous research and in clinical practice that older adults are at an increased risk of falls compared to younger adults (National Health Service, 2021). The reasons for this are highly multifaceted – for example, prescription to certain medications (Callis, 2016), reductions in visual acuity and hearing sensitivity (Reed-Jones et al., 2013; Campos et al., 2018) and age-related muscle loss (Lim & Kong, 2022) all contribute to the weaker balance maintenance often experienced in older adulthood. However, treatments and therapies that have been previously implemented to address each of these factors in clinical practice have only been moderately successful in reducing incidence of falls (Parry et al., 2008; Merriman et al., 2015), suggesting that there may be extrinsic perceptual and cognitive factors at play that also exacerbate fall risk. Injuries associated with falls in the elderly cost the UK National Health Service approximately £4.4 billion per year, and the resulting reduction in independence and balance confidence has a catastrophic effect on an older adult's ability to perform activities of daily living, such as cooking, cleaning and shopping (Office for Health Improvement and Disparities, 2022). Given our increasingly ageing population, it is of utmost importance that cognitive neuroscientists contribute to the ongoing discussion surrounding the role of multisensory integration in balance maintenance, and whether anything can be done, from a neuroscientific standpoint, to reduce the risk of falls in older adults.

Balance maintenance depends on efficient multisensory integration in the central nervous system and the subsequent musculoskeletal responses that stem from this (Katsarkas et al., 1994). Older adults who are identified as fall-prone, or who display weaker functional ability compared to other people their age, are believed to integrate too much task-irrelevant sensory information in their environment (Zhang et al., 2020); in contrast, older adults with strong balance, and younger adults who are not an increased risk of falls, accurately select and weigh the incoming sensory inputs with regards to their relevance, reliability and whether they should be integrated (Zhang et al., 2020). Previous research has suggested that the difficulties older adults have in ignoring task-irrelevant information may increase their distractibility in everyday environments (Setti et al., 2011); paired with the fact that older adults have a larger temporal binding window in which this distracting information could be processed, it would be fair to suggest that these older adults with attentional deficits may be more accident-prone (Setti et al., 2011; Setti et al., 2014). In this way, it is clear how age-related changes in attentional control during audiovisual integration can impact the balance ability and subsequent fall risk of older adults.

Historically, and particularly with regards to younger adults, balance maintenance has been viewed as a largely automatic process involving subcortical brain areas and the brainstem (Dietz et al., 1992). However, healthy ageing often results in the neurodegeneration of subcortical balance centres (Cham et al., 2007; Murray et al., 2010; Papegaaij et al., 2014); consequently, older adults may rely on a compensatory strategy, engaging higher-level cortical brain regions to employ attentional resources as a means of maintaining balance (Ozdemir et al., 2016; Kahya et al., 2019). Indeed, previous research has found that, with increasing age and under challenging balance conditions, an increased amount of cognitive resources are dedicated to balance maintenance; this is supported by the fact that older adults display an increased activation of cortical brain regions (e.g. prefrontal cortex) compared to younger adults in situations where balance is compromised (Kahya et al., 2019; Boisgontier & Nougier, 2013). As such, not only does attention impact fall risk from a distractibility perspective, but it is also important to consider situations in which attentional resources are being competed for. Indeed, the effects of attention on balance maintenance are arguably the most salient during dual-task situations, in which a limited pool of attentional resources must be divided between postural control and any secondary multisensory task (Snijders et al., 2007; Woollacott & Shumway-Cook, 2002).

Dual-task paradigms studying the interplay between cognitive control and mobility often involve asking participants to stand in balance positions of varying degrees of difficulty, and systematically increasing the cognitive load of participants by adding an attentionally-demanding secondary task, such as speech perception (Lajoie et al., 1993). Humans have a limited pool of attentional resources which must be flexibly allocated between ongoing tasks; increasing cognitive load via the addition of a concurrent task may exceed the attentional capacities of older adults, resulting in a weaker performance in both the balance task and the secondary task (Ruffieux et al., 2015; Helfer et al., 2020; Slade et al., 2020). Given the serious implications that a fall can have on the health and wellbeing of older adults, this population tend to adopt a "posture first" approach, prioritising balance maintenance over any concurrent attentionally-demanding task (Ozdemir et al., 2016). Older adults' increased allocation of attentional resources to balance may have a detrimental effect on their performance in the secondary task (Slade et al., 2020; Wingfield, 2016), especially if it a complex multisensory situation such as perceiving speech in a noisy listening environment (Pepper & Nuttall, 2023; Boisgontier & Nougier, 2013). Likewise, if the attentionally-demanding secondary task results in increased distractibility and the insufficient allocation of attentional resources to balance, this can result in an increased risk of falls in older adults (Pepper & Nutall, 2023; Setti et al., 2011; Ruffieux et al., 2015).

Within the brain, balance ability is often studied in relation to the vestibular network, which includes brain areas such as the posterior and anterior insula, the superior temporal gyrus, and the temporoparietal junction – all of which have connections to different sensory cortices and are implicated in multisensory processing (Merriman et al., 2015). It is also important to consider the role of alpha oscillations in balance maintenance. That is, if balance becomes a less automatic process as a function of healthy ageing and begins to require more cognitive resources, it is likely that this will be reflected in increased cortical activity (i.e.

decreased alpha activity) in cognitive-motor brain regions. This has been evidenced in younger adults when balance is compromised. For example, Edwards et al. (2018) measured alpha activity when younger adults stood in balance positions increasing in difficulty – the researchers found that as balance maintenance became more challenging, alpha activity decreased in central and parietal brain regions. These decreases in alpha power indexed an increased activation of central and parietal brain regions in order to facilitate balance, supporting the important role of alpha in attentional control when balance is compromised (Edwards et al., 2018). Despite this interesting finding, there is very little evidence investigating how age-related changes in balance ability and fall risk may be reflected in alpha activity – studying these neural correlates of attention and relating them to balance is key in understanding why, from a neuroscientific perspective, older adults may be at an increased risk of falls.

1.3.2. Real-world implications: speech perception

Balance maintenance is not the only multisensory everyday task that becomes more difficult with increasing age – older adults also find it more difficult than younger adults to understand speech, especially in noisy listening environments (Pichora-Fuller et al., 2017). As has been well-established by research into the cocktail-party effect (Cherry, 1953; Meister et al., 2013), one of the main challenges with understanding speech surrounds the ability to focus attention on the target speaker and inhibit any distracting, irrelevant background noise in the environment. This situation becomes more even more difficult as a function of healthy ageing, not only due to hearing loss within the peripheral auditory system (e.g. degeneration of hair cells in the cochlea, atrophy of spiral ganglion cells, atrophy of the stria vascularis; Slade et al., 2020), but also due to age-related declines in attentional control (Getzmann et al., 2016; Getzmann et al., 2015; Lin & Carlile, 2015; Schneider et al., 2011). The challenges of perceiving speech in noisy listening environments can lead to older adults withdrawing from social situations in which background noise is likely to be present, and can have a significant impact on the mental wellbeing of our elderly population (Nuttall et al., 2022).

Some theories have posited that older adults may employ a compensatory strategy to process degraded auditory information during speech perception. The decline-compensation hypothesis (Wingfield & Grossman, 2006) and the information degradation hypothesis (Schneider & Pichora-Fuller, 2000) suggest that older adults' brains strategically recruit a greater amount of cognitive resources during speech perception, compared to younger adults. That is, to compensate for age-related sensory declines or reduced activation of specialised cortical regions involved in speech (e.g. inferior frontal gyrus; Peelle et al., 2010; Davis & Johnsrude, 2003), older adults may recruit increased cognitive resources to preserve performance (Peelle et al., 2010; Getzmann et al., 2015). Indeed, fMRI and EEG measurements during speech-in-noise perception revealed that older adults displayed increased activation in attentional neural networks (Wong et al., 2009; Getzmann & Falkenstein, 2011). As such, compared to younger adults, older adults appear to rely more heavily on top-down cognitive mechanisms to perceive speech in adverse listening conditions, allocating increased attentional resources and employing more effortful listening strategies to process the auditory signal (Getzmann et al., 2015; Slade et al., 2020).

Whilst some may argue that it is positive that older adults have developed compensatory strategies to preserve their ability to perceive speech, such effortful listening can have a detrimental effect on cognitive function (Humes et al., 2013; Slade et al., 2020). Based on the dual-task methodologies discussed in the previous section, whilst diverting cognitive resources towards speech perception and away from any co-occurring tasks may improve an older adult's ability to process the acoustic signal, this can weaken performance on the secondary task due to the limited availability of cognitive resources (Slade et al., 2020; Ward et al., 2017). Furthermore, in line with the sensory deprivation hypothesis, chronic reallocation of attentional resources towards auditory perception can result in cognitive decline, due to cortical reorganisation which impedes global cognitive functioning in favour of improved acoustic processing (Slade et al., 2020; Lindenberger & Baltes, 1994; Schneider & Pichora-Fuller, 2000). This highlights the importance of studying how younger and older adults may differentially allocate attentional resources, and the impact that this may have on both speech perception performance and neural architecture.

Age-related changes in speech perception have also been investigated with regards to alpha power. Specifically, increases in alpha power may serve to inhibit distracting noise from external sources and background speakers, whilst decreases in alpha power may facilitate attention towards target speech (Wostmann et al., 2017; McMahon et al., 2016; Dimitrijevic et al., 2019). This interplay becomes even more complex when considering the fact that alpha activity may be responsible for different functional roles depending on where it originates in the brain. For example, if the core functional role of alpha activity is to inhibit background noise, it is likely to be driven by parietal brain regions involved in the attentional network

(Wostmann et al., 2017). However, if alpha instead serves to facilitate attention towards target speech, then it is likely to be driven by auditory brain regions in the temporal cortex involved in speech processing (Dimitrijevic et al., 2017). As discussed, if older adults exhibit weaker inhibitory abilities than younger adults during speech perception, it would be fair to suggest that parietal alpha activity is less effective in older adults. Instead, perhaps older adults may rely on auditory alpha activity to a greater degree, compensating for their weaker inhibitory abilities by strengthening their attention towards target speech (Herrmann et al., 2022). Taken together, analysing increases and decreases in alpha activity in different brain areas during speech perception, and how this may differ between younger and older adults, could cast light on the strategies that each age group use to perceive speech in adverse listening environments.

1.4. Thesis Overview and Importance

The perceptual and cognitive mechanisms involved in multisensory integration coordinate in a complex and dynamic manner to create a quick and accurate representation of our environment. The investigation of these mechanisms is made even more important given that elements like temporal precision and attentional control can deteriorate as a function of healthy ageing. Age-related changes in multisensory integration can have a significant impact on key activities of daily living like speech perception and balance maintenance; in order to support our increasingly ageing population, it is imperative that a comprehensive understanding of how the top-down modulation of audiovisual processing differs between younger and older adults, and the effect this has on veridical perception. The most useful account will come from studying age-related changes in key neural correlates of attentional control during multisensory integration – specifically, from measuring the respective increases and decreases in oscillatory alpha power in conditions when distracting sensory information must be inhibited, and when attentional resources must be efficiently allocated according to task demands.

First, this thesis draws together literature investigating audiovisual speech perception and how this changes with healthy ageing (**Chapter 2**). Previous experimental paradigms are critically evaluated and findings surrounding the role of oscillatory alpha activity in the attentional modulation of audiovisual integration are discussed. This review also adopts a novel perspective to identify the shared top-down and bottom-up mechanisms involved in both speech perception and balance maintenance, highlighting how the age-related changes in such mechanisms can significantly impact the quality of life of older adults. **Chapter 3** studies whether younger and older adults can deploy top-down attentional control to influence bottom-up sensory processing through modulating the width of the temporal binding window. To investigate the neural correlates of this, **Chapter 4** then investigates whether the attentional modulation of audiovisual integration could be predicted by alpha power, as well as measuring the association between integration, attentional control and functional balance ability as a proxy for fall risk. **Chapter 5** describes an EEG paradigm involving dual-task speech perception and balance maintenance, comparing performance across both multisensory tasks and analysing alpha activity to understand how the flexible allocation of attentional resources changes with healthy ageing. Finally, to draw causal links between alpha power and the ability to inhibit distracting information during auditory processing, **Chapter 6** employs a TMS-EEG paradigm to investigate whether entraining alpha oscillators could improve an older adults' ability to select and attend to target speech whilst suppressing distracting background speakers. **Chapter 7** then provides a general discussion of the findings uncovered throughout this thesis, highlighting the important implications for our understanding of age-related changes in multisensory processing and postulating directions for future research.

1.5. Rationale for Alternative Format

Chapters 2-6 in this thesis are written in publishable manuscript format. Chapter 2 and Chapter 3 have both been published (Chapter 2 – *Brain Sciences*; Chapter 3 – *Attention, Perception & Psychophysics).* The studies detailed in Chapters 4-6 will be submitted for peer review. Each chapter in this thesis details different investigations into the age-related changes in audiovisual processing, containing both behavioural and neuroscientific findings. The chapters, despite being distinct papers, are logically connected and provide a comprehensive narrative regarding how audiovisual processing changes with healthy ageing, how this may be reflected in alpha activity, and the impact of such changes on speech perception and balance maintenance.

1.6. Author Contributions

For Chapters 2-6 of this thesis, I was involved in the conceptualisation, study design, data collection, data analyses, writing of the manuscript and revision of the manuscript, under the supervision of Dr Helen Nuttall, Dr Theodoros Bampouras, and Dr Jason Braithwaite. In addition, Barrie Usherwood provided technical support for Chapter 3. Dr Bo Yao collaborated on Chapter 4 and 5 with regards to assisting with EEG analysis. Dr Kate Slade, Professor Ingrid Johnsrude, and Dr Bjorn Herrmann collaborated on Chapter 6 with regards experimental design, and Dr Elise Oosterhuis assisted with data collection for Chapter 6.

References

Balz, J., Keil, J., Romero, Y. R., Mekle, R., Schubert, F., Aydin, S., ... & Senkowski, D. (2016). GABA concentration in superior temporal sulcus predicts gamma power and perception in the sound-induced flash illusion. *Neuroimage*, *125*, 724-730.

Baum, S. H., & Stevenson, R. A. (2017). Shifts in audiovisual processing in healthy aging. *Current Behavioral Neuroscience Reports*, *4*, 198-208.

Beauchamp, M. S., Nath, A. R., & Pasalar, S. (2010). fMRI-guided transcranial magnetic stimulation reveals that the superior temporal sulcus is a cortical locus of the McGurk effect. *Journal of Neuroscience*, *30*(7), 2414-2417.

Beauchamp, Michael S. "See me, hear me, touch me: multisensory integration in lateral occipital-temporal cortex." *Current opinion in neurobiology* 15, no. 2 (2005): 145-153.

Bedard, G., & Barnett-Cowan, M. (2016). Impaired timing of audiovisual events in the elderly. *Experimental brain research*, *234*, 331-340.

Bhattacharya, J., Shams, L., & Shimojo, S. (2002). Sound-induced illusory flash perception: role of gamma band responses. *Neuroreport*, *13*(14), 1727-1730.

Boisgontier, M. P., & Nougier, V. (2013). Ageing of internal models: from a continuous to an intermittent proprioceptive control of movement. *Age*, *35*, 1339-1355.

Borghini, G., Candini, M., Filannino, C., Hussain, M., Walsh, V., Romei, V., ... & Cappelletti, M. (2018). Alpha oscillations are causally linked to inhibitory abilities in ageing. *Journal of Neuroscience*, *38*(18), 4418-4429.

Brooks, C. J., Chan, Y. M., Anderson, A. J., & McKendrick, A. M. (2018). Audiovisual temporal perception in aging: The role of multisensory integration and age-related sensory loss. *Frontiers in Human Neuroscience*, *12*, 192.

Bruns, P. (2019). The ventriloquist illusion as a tool to study multisensory processing: An update. *Frontiers in Integrative Neuroscience*, *13*, 51.

Callis, N. (2016). Falls prevention: Identification of predictive fall risk factors. *Applied nursing research*, *29*, 53-58.

Calvert, G. (2004). *The handbook of multisensory processes*. MIT press.

Calvert, G. A., Campbell, R., & Brammer, M. J. (2000). Evidence from functional magnetic resonance imaging of crossmodal binding in the human heteromodal cortex. *Current biology*, *10*(11), 649-657.

Campos, J., Ramkhalawansingh, R., & Pichora-Fuller, M. K. (2018). Hearing, self-motion perception, mobility, and aging. *Hearing research*, *369*, 42-55.

Caspary, D. M., Schatteman, T. A., & Hughes, L. F. (2005). Age-related changes in the inhibitory response properties of dorsal cochlear nucleus output neurons: role of inhibitory inputs. *Journal of Neuroscience*, *25*(47), 10952-10959.

Cham, R., Perera, S., Studenski, S. A., & Bohnen, N. I. (2007). Striatal dopamine denervation and sensory integration for balance in middle-aged and older adults. *Gait & posture*, *26*(4), 516-525.

Chan, Y. M., Pianta, M. J., & McKendrick, A. M. (2014). Reduced audiovisual recalibration in the elderly. *Frontiers in aging neuroscience*, *6*, 226.

Chen, L., & Vroomen, J. (2013). Intersensory binding across space and time: a tutorial review. *Attention, Perception, & Psychophysics*, *75*, 790-811.

Cherry, E.C. Some experiments on the recognition of speech, with one and with two ears. J. Acoust. Soc. Am. 1953, 25, 975–979.

Cornelio, P., Velasco, C., & Obrist, M. (2021). Multisensory integration as per technological advances: A review. *Frontiers in neuroscience*, *15*, 652611.

Curtis, C. E., & D'Esposito, M. (2003). Persistent activity in the prefrontal cortex during working memory. *Trends in cognitive sciences*, *7*(9), 415-423.

De Dieuleveult, A. L., Siemonsma, P. C., Van Erp, J. B., & Brouwer, A. M. (2017). Effects of aging in multisensory integration: a systematic review. *Frontiers in aging neuroscience*, *9*, 80.

DeLoss, D. J., Pierce, R. S., & Andersen, G. J. (2013). Multisensory integration, aging, and the sound-induced flash illusion. *Psychology and aging*, *28*(3), 802.

Dietz, V. O. L. K. E. R. (1992). Human neuronal control of automatic functional movements: interaction between central programs and afferent input. *Physiological reviews*, *72*(1), 33-69.

Dimitrijevic, A., Smith, M. L., Kadis, D. S., & Moore, D. R. (2019). Neural indices of listening effort in noisy environments. *Scientific Reports*, *9*(1), 11278.

Dimitrijevic, A., Smith, M. L., Kadis, D. S., & Moore, D. R. (2017). Cortical alpha oscillations predict speech intelligibility. *Frontiers in human neuroscience*, *11*, 88.

Donohue, S. E., Green, J. J., & Woldorff, M. G. (2015). The effects of attention on the temporal integration of multisensory stimuli. *Frontiers in Integrative Neuroscience*, *9*, 32.

Edwards, A. E., Guven, O., Furman, M. D., Arshad, Q., & Bronstein, A. M. (2018). Electroencephalographic correlates of continuous postural tasks of increasing difficulty. *Neuroscience*, *395*, 35-48.

Fairhall, S.L.; Macaluso, E. Spatial attention can modulate audiovisual integration at multiple cortical and subcortical sites. *Eur. J. Neurosci.* **2009**, *29*, 1247–1257. https://doi.org/10.1111/j.1460-9568.2009.06688.x.

Gazzaley, A., & Nobre, A. C. (2012). Top-down modulation: bridging selective attention and working memory. *Trends in cognitive sciences*, *16*(2), 129-135.

Getzmann, S., Golob, E. J., & Wascher, E. (2016). Focused and divided attention in a simulated cocktail-party situation: ERP evidence from younger and older adults. *Neurobiology of aging*, *41*, 138-149.

Getzmann, S., Jasny, J., & Falkenstein, M. (2017). Switching of auditory attention in "cocktail-party" listening: ERP evidence of cueing effects in younger and older adults. *Brain and cognition*, *111*, 1-12.

Getzmann, S., Wascher, E., & Falkenstein, M. (2015). What does successful speech-in-noise perception in aging depend on? Electrophysiological correlates of high and low performance in older adults. *Neuropsychologia*, *70*, 43-57.

Guerreiro, M. J., Murphy, D. R., & Van Gerven, P. W. (2010). The role of sensory modality in age-related distraction: a critical review and a renewed view. *Psychological bulletin*, *136*(6), 975.

Hasher, L. (1988). Working memory, comprehension, and aging: A review and a new view. *The psychology of learning and motivation*, *22*.

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circadian arousal, and age.

Helfer, K. S., Freyman, R. L., van Emmerik, R., & Banks, J. (2020). Postural control while listening in younger and middle-aged adults. *Ear and hearing*, *41*(5), 1383-1396.

Herrmann, B., Maess, B., Henry, M. J., Obleser, J., & Johnsrude, I. S. (2022). Age-related changes in the neural mechanics of dynamic auditory attention in time. *bioRxiv*, 2022-04.

Hirst, R. J., Setti, A., Kenny, R. A., & Newell, F. N. (2019). Age-related sensory decline mediates the Sound-Induced Flash Illusion: Evidence for reliability weighting models of multisensory perception. *Scientific Reports*, *9*(1), 19347.

Holmes, N. P., & Spence, C. (2005). Multisensory integration: space, time and superadditivity. *Current Biology*, *15*(18), R762-R764.

Humes, L. E., Busey, T. A., Craig, J., & Kewley-Port, D. (2013). Are age-related changes in cognitive function driven by age-related changes in sensory processing?. *Attention, Perception, & Psychophysics*, *75*, 508-524.

Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Frontiers in human neuroscience*, *4*, 186.

Jones, S. A., & Noppeney, U. (2021). Ageing and multisensory integration: A review of the evidence, and a computational perspective. *Cortex*, *138*, 1-23.

Jones, S. A., Beierholm, U., Meijer, D., & Noppeney, U. (2019). Older adults sacrifice response speed to preserve multisensory integration performance. *Neurobiology of aging*, *84*, 148-157.

Kahya, M., Moon, S., Ranchet, M., Vukas, R. R., Lyons, K. E., Pahwa, R., ... & Devos, H. (2019). Brain activity during dual task gait and balance in aging and age-related neurodegenerative conditions: a systematic review. *Experimental gerontology*, *128*, 110756.

Katsarkas, A. (1994). Dizziness in aging: a retrospective study of 1194 cases. *Otolaryngology—Head and Neck Surgery*, *110*(3), 296-301.

Keil, J., & Senkowski, D. (2018). Neural oscillations orchestrate multisensory processing. *The Neuroscientist*, *24*(6), 609-626.

Klatt, L. I., Schneider, D., Schubert, A. L., Hanenberg, C., Lewald, J., Wascher, E., & Getzmann, S. (2020). Unraveling the relation between EEG correlates of attentional orienting and sound localization performance: a diffusion model approach. *Journal of Cognitive Neuroscience*, *32*(5), 945-962.

LaBerge, D. (1995). *Attentional processing: The brain's art of mindfulness*. Harvard University Press.

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1993). Attentional demands for static and dynamic equilibrium. *Experimental brain research*, *97*, 139-144.

Lange, J., Oostenveld, R., & Fries, P. (2011). Perception of the touch-induced visual double-flash illusion correlates with changes of rhythmic neuronal activity in human visual and somatosensory areas. *Neuroimage*, *54*(2), 1395-1405.

Laurienti, P. J., Burdette, J. H., Maldjian, J. A., & Wallace, M. T. (2006). Enhanced multisensory integration in older adults. *Neurobiology of aging*, *27*(8), 1155-1163.

Laurienti, P. J., Kraft, R. A., Maldjian, J. A., Burdette, J. H., & Wallace, M. T. (2004). Semantic congruence is a critical factor in multisensory behavioral performance. *Experimental brain research*, *158*, 405-414.

Lim, S. K., & Kong, S. (2022). Prevalence, physical characteristics, and fall risk in older adults with and without possible sarcopenia. *Aging clinical and experimental research*, *34*(6), 1365-1371.

Lin, G., & Carlile, S. (2015). Costs of switching auditory spatial attention in following conversational turn-taking. *Frontiers in Neuroscience*, *9*, 124.

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: a strong connection. *Psychology and aging*, *9*(3), 339.

Lustig, C., & Hasher, L. (2001). Implicit memory is not immune to interference. *Psychological Bulletin*, *127*(5), 618.

Lustig, C., Hasher, L., & Zacks, R. T. (2007). Inhibitory deficit theory: recent developments in a" new view".

Mahoney, J. R., Holtzer, R., & Verghese, J. (2014). Visual-somatosensory integration and balance: evidence for psychophysical integrative differences in aging. *Multisensory research*, *27*(1), 17-42.

McGovern, D. P., Roudaia, E., Stapleton, J., McGinnity, T. M., & Newell, F. N. (2014). The sound-induced flash illusion reveals dissociable age-related effects in multisensory integration. *Frontiers in aging neuroscience*, *6*, 250.

McMahon, C. M., Boisvert, I., De Lissa, P., Granger, L., Ibrahim, R., Lo, C. Y., ... & Graham, P. L. (2016). Monitoring alpha oscillations and pupil dilation across a performance-intensity function. *Frontiers in Psychology*, *7*, 745.

Meister, H., Schreitmüller, S., Grugel, L., Beutner, D., Walger, M., & Meister, I. (2013). Examining speech perception in noise and cognitive functions in the elderly.

Meredith, M. A., & Stein, B. E. (1985). Descending efferents from the superior colliculus relay integrated multisensory information. *Science*, *227*(4687), 657-659.

Meredith, M. A., & Stein, B. E. (1996). Spatial determinants of multisensory integration in cat superior colliculus neurons. *Journal of neurophysiology*, *75*(5), 1843-1857.

Meredith, M. A., Nemitz, J. W., & Stein, B. E. (1987). Determinants of multisensory integration in superior colliculus neurons. I. Temporal factors. *Journal of Neuroscience*, *7*(10), 3215-3229.

Meredith, M. A., Wallace, M. T., & Stein, B. E. (1992). Visual, auditory and somatosensory convergence in output neurons of the cat superior colliculus: multisensory properties of the tecto-reticulo-spinal projection. *Experimental Brain Research*, *88*, 181-186.

Merriman, N. A., Whyatt, C., Setti, A., Craig, C., & Newell, F. N. (2015). Successful balance training is associated with improved multisensory function in fall-prone older adults. *Computers in human behavior*, *45*, 192-203.

Mishra, J., Martinez, A., Sejnowski, T. J., & Hillyard, S. A. (2007). Early cross-modal interactions in auditory and visual cortex underlie a sound-induced visual illusion. *Journal of Neuroscience*, *27*(15), 4120-4131.

Mozolic, J. L., Hugenschmidt, C. E., Peiffer, A. M., & Laurienti, P. J. (2008). Modality-specific selective attention attenuates multisensory integration. *Experimental brain research*, *184*, 39-52.

Mozolic, J. L., Hugenschmidt, C. E., Peiffer, A. M., & Laurienti, P. J. (2012). Multisensory integration and aging.

Murray, M. E., Senjem, M. L., Petersen, R. C., Hollman, J. H., Preboske, G. M., Weigand, S. D., ... & Jack, C. R. (2010). Functional impact of white matter hyperintensities in cognitively normal elderly subjects. *Archives of neurology*, *67*(11), 1379-1385.

Murray, M. M., Lewkowicz, D. J., Amedi, A., & Wallace, M. T. (2016). Multisensory processes: a balancing act across the lifespan. *Trends in neurosciences*, *39*(8), 567-579.

National Health Service. (2021). *Falls.* https://www.nhs.uk/conditions/falls/

Nuttall, H. E., Maegherman, G., Devlin, J. T., & Adank, P. (2022). Speech motor facilitation is not affected by ageing but is modulated by task demands during speech perception. *Neuropsychologia*, *166*, 108135.

Office for Health Improvement and Disparities. (2022, February). *Falls: Applying All Our Health.* Gov.uk. Available online: https://www.gov.uk/government/publications/falls-applying-all-our-health/falls-applying-all-our-health (accessed on 2 March 2022).

O'Sullivan, A. E., Lim, C. Y., & Lalor, E. C. (2019). Look at me when I'm talking to you: Selective attention at a multisensory cocktail party can be decoded using stimulus reconstruction and alpha power modulations. *European Journal of Neuroscience*, *50*(8), 3282-3295.

Ozdemir, R. A., Contreras-Vidal, J. L., Lee, B. C., & Paloski, W. H. (2016). Cortical activity modulations underlying age-related performance differences during posture–cognition dual tasking. *Experimental brain research*, *234*, 3321-3334.

Papegaaij, S., Taube, W., Baudry, S., Otten, E., & Hortobágyi, T. (2014). Aging causes a reorganization of cortical and spinal control of posture. *Frontiers in aging neuroscience*, *6*, 28.

Park, H., Nannt, J., & Kayser, C. (2021). Sensory-and memory-related drivers for altered ventriloquism effects and aftereffects in older adults. *Cortex*, *135*, 298-310.

Peelle, J. E., Troiani, V., Wingfield, A., & Grossman, M. (2010). Neural processing during older adults' comprehension of spoken sentences: age differences in resource allocation and connectivity. *Cerebral cortex*, *20*(4), 773-782.

Peiffer, A. M., Mozolic, J. L., Hugenschmidt, C. E., & Laurienti, P. J. (2007). Age-related multisensory enhancement in a simple audiovisual detection task. *Neuroreport*, *18*(10), 1077-1081.

Pepper, J. L., & Nuttall, H. E. (2023). Age-related changes to multisensory integration and audiovisual speech perception. *Brain Sciences*, *13*(8), 1126.

Pepper, J. L., Usherwood, B., Bampouras, T. M., & Nuttall, H. E. (2023). Age-related changes to the attentional modulation of temporal binding. *Attention, Perception, & Psychophysics*, *85*(6), 1905-1919.

Pichora-Fuller, M. K., Alain, C., & Schneider, B. A. (2017). Older adults at the cocktail party. *The auditory system at the cocktail party*, 227-259.

Posner, M. I., & Driver, J. (1992). The neurobiology of selective attention. *Current opinion in neurobiology*, *2*(2), 165-169.

Powers, A. R., Hevey, M. A., & Wallace, M. T. (2012). Neural correlates of multisensory perceptual learning. *Journal of Neuroscience*, *32*(18), 6263-6274.

Ramkhalawansingh, R., Keshavarz, B., Haycock, B., Shahab, S., & Campos, J. L. (2016). Age differences in visual-auditory self-motion perception during a simulated driving task. *Frontiers in psychology*, *7*, 595.

Reed-Jones, R. J., Solis, G. R., Lawson, K. A., Loya, A. M., Cude-Islas, D., & Berger, C. S. (2013). Vision and falls: a multidisciplinary review of the contributions of visual impairment to falls among older adults. *Maturitas*, *75*(1), 22-28.

Rowland, B. A., Stanford, T. R., & Stein, B. E. (2007). A model of the neural mechanisms underlying multisensory integration in the superior colliculus. *Perception*, *36*(10), 1431-1443.

Ruffieux, J., Keller, M., Lauber, B., & Taube, W. (2015). Changes in standing and walking performance under dual-task conditions across the lifespan. *Sports Medicine*, *45*, 1739-1758.

Sander, M. C., Werkle-Bergner, M., & Lindenberger, U. (2012). Amplitude modulations and inter-trial phase stability of alpha-oscillations differentially reflect working memory constraints across the lifespan. *Neuroimage*, *59*(1), 646-654.

Schneider, B. A. (2011). How age affects auditory-cognitive interactions in speech comprehension. *Audiology Research*, *1*(1).

Schneider, B. A., & Pichora-Fuller, M. K. (2000). Implications of perceptual deterioration for cognitive aging research.

Scurry, A. N., Lovelady, Z., Lemus, D. M., & Jiang, F. (2021). Impoverished inhibitory control exacerbates multisensory impairments in older fallers. *Frontiers in aging neuroscience*, *13*, 700787.

Setti, A., Burke, K. E., Kenny, R. A., & Newell, F. N. (2011). Is inefficient multisensory processing associated with falls in older people?. *Experimental brain research*, *209*, 375-384.

Setti, A., Stapleton, J., Leahy, D., Walsh, C., Kenny, R. A., & Newell, F. N. (2014). Improving the efficiency of multisensory integration in older adults: audio-visual temporal discrimination training reduces susceptibility to the sound-induced flash illusion. *Neuropsychologia*, *61*, 259-268.

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Measurement of attentional reserve and mental effort for cognitive workload assessment under various task demands during dual-task walking. *Biological psychology*, *134*, 39-51.

Slade, K., Plack, C. J., & Nuttall, H. E. (2020). The effects of age-related hearing loss on the brain and cognitive function. *Trends in Neurosciences*, *43*(10), 810-821.

Snijders, A. H., Van De Warrenburg, B. P., Giladi, N., & Bloem, B. R. (2007). Neurological gait disorders in elderly people: clinical approach and classification. *The Lancet Neurology*, *6*(1), 63-74.

Spence, C. (2007). Audiovisual multisensory integration. *Acoustical science and technology*, *28*(2), 61-70.

Spence, C. (2013). Just how important is spatial coincidence to multisensory integration? Evaluating the spatial rule. *Annals of the New York Academy of Sciences*, *1296*(1), 31-49.

Stanford, T. R., Quessy, S., & Stein, B. E. (2005). Evaluating the operations underlying multisensory integration in the cat superior colliculus. *Journal of Neuroscience*, *25*(28), 6499-6508.

Stawicki, M., Majdak, P., & Başkent, D. (2019). Ventriloquist illusion produced with virtual acoustic spatial cues and asynchronous audiovisual stimuli in both young and older individuals. *Multisensory research*, *32*(8), 745-770.

Stein, B. E. (1993). *The Merging of the Senses*. MIT Press.

Stevenson, R. A., & James, T. W. (2009). Audiovisual integration in human superior temporal sulcus: Inverse effectiveness and the neural processing of speech and object recognition. *Neuroimage*, *44*(3), 1210-1223.

Stevenson, R. A., Baum, S. H., Krueger, J., Newhouse, P. A., & Wallace, M. T. (2018). Links between temporal acuity and multisensory integration across life span. *Journal of experimental psychology: human perception and performance*, *44*(1), 106.

Talsma, D. (2015). Predictive coding and multisensory integration: an attentional account of the multisensory mind. *Frontiers in Integrative Neuroscience*, *9*, 19.

Talsma, D., & Woldorff, M. G. (2005). Selective attention and multisensory integration: multiple phases of effects on the evoked brain activity. *Journal of cognitive neuroscience*, *17*(7), 1098-1114.

Talsma, D., Doty, T. J., & Woldorff, M. G. (2007). Selective attention and audiovisual integration: is attending to both modalities a prerequisite for early integration?. *Cerebral cortex*, *17*(3), 679-690.

Talsma, D., Senkowski, D., Soto-Faraco, S., & Woldorff, M. G. (2010). The multifaceted interplay between attention and multisensory integration. *Trends in cognitive sciences*, *14*(9), 400-410.

Venezia, J. H., Vaden Jr, K. I., Rong, F., Maddox, D., Saberi, K., & Hickok, G. (2017). Auditory, visual and audiovisual speech processing streams in superior temporal sulcus. *Frontiers in Human Neuroscience*, *11*, 174.

Vroomen, J., & Keetels, M. (2010). Perception of intersensory synchrony: a tutorial review. *Attention, Perception, & Psychophysics*, *72*(4), 871-884.

Wallace, M. T., & Stein, B. E. (1997). Development of multisensory neurons and multisensory integration in cat superior colliculus. *Journal of Neuroscience*, *17*(7), 2429-2444.

Wallace, M. T., & Stevenson, R. A. (2014). The construct of the multisensory temporal binding window and its dysregulation in developmental disabilities. *Neuropsychologia*, *64*, 105-123.

Ward, K. M., Shen, J., Souza, P. E., & Grieco-Calub, T. M. (2017). Age-related differences in listening effort during degraded speech recognition. *Ear and Hearing*, *38*(1), 74-84.

Wingfield, A. (2016). Evolution of models of working memory and cognitive resources. *Ear and hearing*, *37*, 35S-43S.

Wingfield, A., & Grossman, M. (2006). Language and the aging brain: patterns of neural compensation revealed by functional brain imaging. *Journal of neurophysiology*, *96*(6), 2830-2839.

Wong, P. C., Jin, J. X., Gunasekera, G. M., Abel, R., Lee, E. R., & Dhar, S. (2009). Aging and cortical mechanisms of speech perception in noise. *Neuropsychologia*, *47*(3), 693-703.

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait & posture*, *16*(1), 1-14.

Wöstmann, M., Herrmann, B., Wilsch, A., & Obleser, J. (2015). Neural alpha dynamics in younger and older listeners reflect acoustic challenges and predictive benefits. *Journal of Neuroscience*, *35*(4), 1458-1467.

Wöstmann, M., Lim, S. J., & Obleser, J. (2017). The human neural alpha response to speech is a proxy of attentional control. *Cerebral cortex*, *27*(6), 3307-3317.

Wright, T. M., Pelphrey, K. A., Allison, T., McKeown, M. J., & McCarthy, G. (2003). Polysensory interactions along lateral temporal regions evoked by audiovisual speech. *Cerebral cortex*, *13*(10), 1034-1043.

Zhang, S., Xu, W., Zhu, Y., Tian, E., & Kong, W. (2020). Impaired multisensory integration predisposes the elderly people to fall: a systematic review. *Frontiers in neuroscience*, *14*, 411.

2. Age-Related Changes to Multisensory Integration and Audiovisual Speech Perception

2.1. Linking Statement

Chapter 2 consists of a detailed literature review providing a novel perspective on the shared mechanisms involved in audiovisual integration for speech processing and fall risk in older adults. A central topic in the review was the role of oscillatory alpha activity in audiovisual integration. Through critically analysing experimental paradigms and drawing together key findings, this review combines neuroscientific research surrounding age-related changes in audiovisual processing, to uncover important common factors involved in the weaker speech perception and increased fall risk in older adults. The key bottom-up and top-down mechanisms involved in multisensory integration are discussed, with a specific emphasis on exploring the interplay between temporal precision and attentional control. Crucially, the review identifies how this interplay may change as a function of healthy ageing, and the impact that such changes can have on an older adult's perception and action in everyday life.

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Review

Age-Related Changes to Multisensory Integration and Audiovisual Speech Perception

Jessica L. Pepper and Helen E. Nuttall *

Department of Psychology, Lancaster University, Bailrigg LA1 4YF, UK; j.l.pepper@lancaster.ac.uk
* Correspondence: h.nuttall1@lancaster.ac.uk

Abstract: Multisensory integration is essential for the quick and accurate perception of our environment, particularly in everyday tasks like speech perception. Research has highlighted the importance of investigating bottom-up and top-down contributions to multisensory integration and how these change as a function of ageing. Specifically, perceptual factors like the temporal binding window and cognitive factors like attention and inhibition appear to be fundamental in the integration of visual and auditory information—integration that may become less efficient as we age. These factors have been linked to brain areas like the superior temporal sulcus, with neural oscillations in the alpha-band frequency also being implicated in multisensory processing. Age-related changes in multisensory integration may have significant consequences for the well-being of our increasingly ageing population, affecting their ability to communicate with others and safely move through their environment; it is crucial that the evidence surrounding this subject continues to be carefully investigated. This review will discuss research into age-related changes in the perceptual and cognitive mechanisms of multisensory integration and the impact that these changes have on speech perception and fall risk. The role of oscillatory alpha activity is of particular interest, as it may be key in the modulation of multisensory integration.

Keywords: multisensory; ageing; speech; temporal binding; attention; inhibition; alpha activity; falls

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2.2. Multisensory Integration

Multisensory integration encompasses the mechanisms involved when information is processed by individual sensory systems and combined into a coherent perceptual event [1]. Accurate and reliable multisensory integration is dependent on the spatial and temporal proximity of stimuli from different modalities [2,3]. If visual and auditory inputs are presented closely together in time and space, there is an increased likelihood that they will be perceived as occurring from the same event and integrated, to the benefit of perceptual performance [4–6]. The precise and timely binding of congruent sensory information is therefore essential for enabling humans to make sense of their physical environment and successfully perform important everyday tasks [7–9], such as participating in hobbies, mobility and balance, and speech perception [10,11].

Not only do older adults experience declines in vision and hearing function, but age-related changes in neurobiology also result in differences in how people process sensory information; these changes have a significant impact on both our ability to perceive speech and our ability to safely move through our environment. Difficulties in understanding speech in noisy environments is a predominant complaint of older adults, which can negatively affect mental well-being due to withdrawing from social situations where speech perception is challenging [12,13]. This reduced socialisation is exacerbated by the difficulties in mobility associated with ageing; older adults experience an increased risk of falls compared to younger adults, which is intrinsically linked to age-related changes in multisensory processing. Over one-third of people over 65 will experience a fall this year, and on average, injuries caused by falls cost the UK's National Health Service over GBP 4.4 billion each year [14]. Due to our increasingly ageing population, studying how the bottom-up and top-down mechanisms of multisensory integration change as a function of healthy ageing has become a high priority in current cognitive neuroscience research [7,15], with the aim of understanding how to potentially strengthen the efficacy of older adults' perception and improve their ability to quickly and accurately interpret their dynamic, multisensory environment.

If visual and auditory inputs are congruent and should conceptually be bound together, the integration of these unisensory cues produces behavioural enhancements. Within both laboratory and naturalistic tasks, such enhancements often manifest as increased accuracy or faster reaction times in response to multisensory stimuli compared to unisensory stimuli [16–18]. The most significant multisensory benefits are often reported when the unisensory stimulus elicits a particularly weak or noisy response when presented on its own [19]. In other words, many researchers have concluded that multisensory enhancements are most apparent when the unisensory stimuli are ambiguous [16].

Previous research suggests that older adults display increased multisensory integration and greater multisensory enhancements relative to younger adults [16,20,21]. When presented with multisensory stimuli versus unisensory stimuli, older adults show greater increases in accuracy and speeded reaction times compared to baseline, more so than the enhancements exhibited by younger adults. It would be reasonable to initially suggest that the multisensory benefits that older adults exhibit could be due to the deterioration of sensory function that is associated with healthy ageing [18]. For example, as we get older, humans experience declines in visual acuity [22,23], which could manifest as older adults requiring more light to see clearly, having difficulty reading or focussing on nearby objects, and changes in colour perception [24]. In addition, older adults experience declines in auditory sensitivity at all frequencies, which results in a less accurate acoustic performance in everyday tasks such as speech discrimination [22,25,26]. Taken together, age-related declines in sensory function may mean that unisensory information may be noisy and must be supported by stimuli from a different modality [15,27,28]. As such, preliminary research in this area focussed on explaining older adults' multisensory benefits through theories akin to the principle of inverse effectiveness—if the auditory or visual inputs are ambiguous due to age-related declines in vision and hearing, perhaps the gains produced when more sensory information is presented together are greater than when strong stimuli are presented individually [29]. However, after comparing participants' reaction times in unisensory and multisensory discrimination trials to those predicted by the independent race model [30,31], Laurienti et al. [16] found that older adults' multisensory enhancements could not be explained by age-related sensory impairments alone.

As such, whilst the exact reason as to how and why older adults exhibit such multisensory enhancements remains unknown, research is beginning to move away from the principle of inverse effectiveness as the sole explanation [16,25], creating space for emerging theories that provide a more comprehensive account of how healthy ageing can affect perception and action.

The objective of this narrative review is to examine how audiovisual integration for speech processing is affected by healthy ageing. Through critically analysing paradigms used in previous research and drawing together key findings, the following sections will provide a novel perspective on the associations between audiovisual integration, speech perception, and fall risk in older adults. To our knowledge, this is the first narrative review to explicitly highlight the shared attentional and perceptual mechanisms involved in speech perception and fall risk, with a predominant focus on the role of oscillatory alpha activity in audiovisual integration. Comprehensively combining neuroscientific research surrounding age-related changes in speech perception and fall risk should uncover important common factors regarding the modulation of audiovisual processing, in key real-world contexts. As such, this review will not only aid in providing directions for future research but will also underline the impact that multisensory changes jointly have on speech perception, mobility and the overall quality of life of older adults.

2.3. Temporal Precision in Multisensory Integration

A key bottom-up factor that influences whether two sensory inputs are bound together is their temporal proximity. The time range within which visual and auditory information can be presented, perceived as simultaneous and subsequently bound together is known as the temporal binding window (TBW). The TBW is a mechanism used by the brain to accept naturally occurring stimulus asynchrony (e.g., due to differences in the speeds of light and sound [32]); this means that if two sensory inputs should veridically be integrated due to occurring from the same event, they are able to be integrated, even if they are not processed at exactly the same time [5,33–35]. Crucially, as stimulus onset asynchrony (SOA) increases—the time difference between the presentation of visual stimuli and auditory stimuli—the likelihood of multisensory integration decreases [36,37]. This highlights the importance of the TBW in accurately and timely multisensory integration and the global perception of our environment. For example, with regards to speech perception, we produce the most accurate percept of the words being spoken to us when we combine the visual input of the speaker's mouth moving with the auditory input of the words being vocalised—we can successfully bind these inputs together because they are congruent, they are spatially proximal, and they fall within the TBW [2,38].

An important finding in recent years is that older adults have a wider TBW than younger adults [33,39–43]. As such, the TBW could be fundamental in explaining why older adults demonstrate increased integration [44]. Ultimately, due to their wider TBW, older adults have a larger time frame over which integration can occur, thus displaying an increased likelihood of binding sensory signals that are asynchronous and failing to ignore incongruent information [5]. Likewise, due to the narrower TBW of younger adults, they demonstrate greater temporal precision in tasks where successful performance depends upon segregating asynchronous audiovisual inputs—that is, identifying when stimuli from two different modalities should remain separate [5].

2.4. How Do We Measure Audiovisual Integration?

Mechanisms that impact multisensory integration, like the TBW, are often studied in research through the use of psychophysical illusions. For example, in the sound-induced flash illusion, participants are presented with a single visual flash and two auditory beeps, and are asked to report the number of flashes they observed [45]; when the visual and auditory inputs are presented in close temporal proximity, the multisensory illusion induces the perception that two flashes are presented rather than one [45]. Setti et al. [46] and Hirst et al. [28] implemented the sound-induced flash illusion and found that older adults were more susceptible to the illusory effects at longer SOAs than younger adults, integrating visual and auditory information more frequently than younger adults even though the inputs were not temporally aligned [5]. The illusion indicates the maximum SOAs in which stimuli can be presented and still be integrated [43], as well as highlighting the difficulties older adults have in discriminating temporal order and simultaneity compared to younger adults [42,46]. Some researchers have postulated that the increased susceptibility to the sound-induced flash illusion in older adults may be due to an increased reliance on multisensory integration, compensating for weak unisensory information due to age-related sensory declines, which is in line with theories like the principle of inverse effectiveness [7,47–49]. However, recent criticisms from Basharat et al. [50] suggest that the sound-induced flash illusion may not be a sufficiently sensitive measure, potentially underestimating the extent to which multisensory integration can occur.

An alternative psychophysical illusion that appears to be generating increasing support for its ability to provide insight into the bottom-up and top-down mechanisms involved in multisensory integration is the stream–bounce illusion, which uses dynamic rather than static stimuli and thus may provide a more ecologically valid indication of how people may perceive their dynamic everyday environment [51,52]. In the illusion, if an irrelevant sound is played at the same time as two moving circles touch, participants are more prone to binding the visual intersection and the auditory tone together, resulting in the percept of the circles bouncing off each other. Increasing the SOA between the sound playing and the circles touching generally decreases the likelihood of participants perceiving the circles to bounce [53]. This example of audiovisual integration is a phenomenon known as the auditory bounce effect [53– 56]. Importantly, brain regions believed to be involved in multisensory integration, such as the superior colliculus and the posterior parietal cortex, display increased activation when the circles are perceived to bounce compared to when they are perceived to stream [55], as well as transcranial magnetic stimulation (TMS) to the right posterior parietal cortex decreasing the likelihood of the participant perceiving the circles to bounce [56]. As such, the stream–bounce illusion has proven to be a highly useful paradigm to investigate both the perceptual and cognitive elements of dynamic multisensory integration.

Focussing specifically on speech perception, arguably the most renowned illusion used to measure audiovisual integration is the McGurk effect [57]. In the McGurk effect, simultaneously presenting the visual input of a speaker articulating the sound/ga/with the auditory input of/ba/often results in the fused “McGurk” percept of “da” [58], indicating that participants bound the incongruent visual and auditory inputs together. Measuring susceptibility to the McGurk effect in different populations, and in clear or noisy listening environments, allows researchers to draw comparisons regarding the extent of multisensory integration between groups. Older adults may exhibit an enhanced McGurk effect compared to younger adults—when auditory and visual inputs are incongruent (and therefore should, in theory, remain separate), older adults bind these inputs together more frequently than younger adults do [59,60]. More than 71% of adults aged over 70 experience age-related hearing loss [12]; some researchers have hypothesised that to compensate for this, older adults may allocate more attentional resources to alternative modalities, like vision, to interpret acoustic information [59,61–63]. Indeed, older adults may undergo cross-modal cortical re-organisation due to age-related hearing loss, whereby auditory cortical regions such as the superior temporal gyrus receive reduced stimulation and may be more extensively recruited by the visual modality [12,64–67]. The increased resources available to the visual modality means that older adults may be able to rely on vision to support the auditory system in disambiguating speech [12,64,67–70]. In the McGurk effect, increased attention to visual inputs would result in a higher number of fused McGurk percepts in older adults.

However, at this point, it is important to note that many studies have found a similar susceptibility to the McGurk effect between younger and older adults. Some researchers have noted that the unisensory declines that naturally occur with healthy ageing, and the individual differences in factors such as education levels of participants, mean that comparisons between younger and older adults regarding their multisensory integration in a McGurk task can be challenging due to variability within age groups [15,44,59,71–73]. In addition, the McGurk has been criticised as being too simplistic and abstract in its representation of how multisensory speech perception happens in everyday life [74–76]. For example, the use of individual syllables and incongruent auditory and visual inputs are not elements that listeners experience in naturalistic conversations, casting doubt on whether the McGurk effect is an ecologically valid way to study veridical speech perception [74,75,77].

As such, some researchers are beginning to move away from McGurk as a measure of audiovisual speech perception and have instead explored alternative ways in which realistic multisensory integration can be investigated (see [74] for a review). For example, Peelle et al. [78] conducted an fMRI study in which auditory-only, visual-only and audiovisual whole words were presented in differing levels of background noise; the researchers found that the functional connectivity between the visual cortex and the auditory cortex was stronger in audiovisual conditions than in the unisensory conditions, a neural indication that participants were binding visual and auditory inputs together. Applying background noise increases the ambiguity of auditory information and is therefore an effective way to engage and subsequently measure multisensory integration in challenging conditions due to the increased reliance on vision [74,78]. Indeed, this technique can also be applied to visual paradigms, manipulating the clarity of the visual input (e.g., increasing blurriness) and measuring the effect on multisensory integration due to the increased reliance on audition [74,79]. Whilst age-related changes in speech-in-noise perception have regularly been investigated using auditory-only paradigms, there is also a large amount of important research analysing how visual information is used to support the auditory system in disambiguating acoustic information in noisy environments. Given the multisensory focus of the current review, we predominantly examine speech perception experiments that have implemented audiovisual paradigms.

As discussed earlier, combining congruent visual and auditory information results in multisensory enhancements—audiovisual information has been found to improve the ability to perceive speech compared to unisensory inputs or incongruent audiovisual inputs [73,80,81]. However, research into age-related changes in audiovisual integration for speech perception has generated mixed findings, particularly due to individual differences in unisensory acuity and cognitive function between participants, and the type of speech stimuli used (e.g., full words, full sentences or phonemes [82,83]). Certainly, for simple stimuli such as flashes and beeps, older adults are able to compensate for age-related declines in visual acuity and hearing sensitivity by integrating information from each modality to produce a quick and accurate multisensory performance [16,82]. However, in more complex scenarios like speech perception in ambiguous conditions, age-related declines in audiovisual integration become apparent [80,84]. For example, Tye-Murray et al. [85] and Gordon and Allen [86] found that whilst younger and older adults displayed equivalent multisensory enhancements when presented with clear audiovisual speech stimuli, older adults showed smaller multisensory enhancements compared to younger adults when the congruent visual inputs were degraded. Similarly, in an audiovisual speech-in-noise task, Stevenson et al. [82] found that older adults showed smaller multisensory benefits compared to younger adults for whole-word recognition when the auditory inputs were degraded (i.e., signal-to-noise ratio was lower); however, for the easier task of phoneme recognition, older and younger adults displayed equivalent increases in multisensory benefits in noisy listening environments. Not only do these findings highlight how audiovisual integration can serve as a compensatory mechanism used to facilitate speech perception, but they also indicate that the ability to detect age-related changes in audiovisual speech perception is dependent upon the complexity of speech stimuli implemented in each experimental paradigm. Future researchers must be mindful of designing a speech perception task that is too simplistic and consider taking steps to avoid ‘ceiling effects’; easy speech perception tasks with a very high accuracy rate make it difficult to identify significant differences in performance between unisensory and audiovisual conditions, and differences between younger and older adults in their multisensory enhancements [80,87,88].

Each of the psychophysical methods discussed have their critics; however, they have provided valuable contributions in measuring the extent to which visual and auditory information can be integrated and the temporal factors that influence such integration. It is likely that utilising paradigms that involve dynamic stimuli (like the stream–bounce illusion), or that reflect naturalistic speech perception, would produce results with more real-world resemblance than experiments that simply use static flashes and beeps; this would provide greater insight into how the perceptual changes that come with healthy ageing affect the ability of older adults to successfully navigate through their dynamic, multisensory environment [89].

2.5. Attentional Modulation of Audiovisual Integration

If older adults are prone to erroneous increased integration, it is important to study whether there are any mechanisms or processes that could be employed to modulate the multisensory integration of older adults, improving their precision by reducing the influence of irrelevant sensory information. One potential top-down mechanism that is generating increasing interest with regards to the modulation of multisensory integration is attentional control [90]. Specifically, selective attention is believed to enhance the perception of sensory information that is task-relevant and suppress the processing of noisy, irrelevant sensory information that should not be incorporated into the percept [91,92]. When multiple sensory modalities are receiving lots of competing inputs, top-down selective attention is essential for multisensory integration between the congruent stimuli [1,93]. If multimodal inputs are congruent, multisensory integration is facilitated (i.e., more accurate responses, faster reaction times); however, if the inputs are incongruent, attention can correctly impede integration [1]. For example, in a multisensory fMRI study involving audiovisual speech, Fairhall and Macaluso [94] found that when attention was directed towards visual lip movements that were congruent with the auditory sentence being played, this improved performance and resulted in increased activation in multisensory brain areas such as the superior temporal sulcus and the superior colliculus, compared to the brain activity when attention was directed towards incongruent lip-movements.

These attentional mechanisms are clearly highly relevant to multisensory speech perception and how our ability to integrate audiovisual information may change as a function of ageing [90,95]—attention to relevant inputs and inhibition of irrelevant inputs are crucial in the quick and accurate processing of audiovisual speech [87,96,97]. For example, it is well-established that under cocktail-party conditions (i.e., segregating and attending to one speech source amongst multiple speakers [98]), accurate speech perception requires the listener to simultaneously direct attentional resources to the target speaker and suppress the distracting, irrelevant information of background speakers or other external noise in the environment [99,100].

The ability to inhibit distracting and irrelevant information in situations like this may weaken as we grow older [101–108]. This is known as the inhibitory deficit hypothesis—an increased processing and subsequent integration of irrelevant sensory information due to the reduced ability to ignore [109]. If this is the case for older adults, perhaps the weakening of inhibitory abilities could be an explanatory factor for their reduced speech-in-noise perception abilities; older adults may find it more difficult to ignore task-irrelevant information and therefore display increased integration relative to younger adults [87,110,111].

However, there is conflicting evidence for the theory that inhibition changes with healthy ageing—research conducted by Hugenschmidt et al. [112] and Guerreiro et al. [113–115] indicates that the ability to ignore distracting information is preserved with healthy ageing. As such, further research is required to determine whether older adults display weaker inhibitory abilities compared to younger adults when presented with visual and auditory information. At the moment, the mixed literature indicates that such findings may be both task-specific and modality-dependent. Nevertheless, if older adults potentially have difficulty in effectively deploying attentional resources to the task at hand, the subsequent reduced regulation of multisensory interactions could be the underlying cause of the wider (less restricted) TBW and the increased multisensory integration exhibited by older adults relative to younger adults [25].

2.6. Multisensory Integration, Attentional Control, and Falls

An emerging theory as to why older adults display increased multisensory integration is focussed on this combination of the potentially weaker inhibitory control and wider TBW of older adults and whether it is associated with their increased risk of falls [33,42,46]. As discussed, older adults may be inefficient in allocating the attentional resources required to sufficiently narrow the TBW and modulate sensory processing, resulting in increased integration of visual and auditory stimuli that may be asynchronous and irrelevant [44,46]. This can lead to dangerously inaccurate perceptions of an older adult's environment, resulting in a fall.

It is important to note that there are many multifaceted risk factors associated with falls in older adults. For example, age-related muscle loss [116], medications that cause light-headedness or vertigo [117], and age-related unisensory declines [118,119] all contribute significantly to the weaker balance maintenance and increased risk of falls in older adults compared to younger adults. However, crucially, stable balance, alongside musculoskeletal demands, is also dependent upon the accurate integration of reliable sensory information in the brain [89,120]. In older adults, not only is balance made more challenging by declines in unisensory acuity, but declines in the efficacy and reliability of multisensory integration mechanisms like attentional control are also likely to negatively impact balance and fall risk. When fall-prone older adults are required to simultaneously maintain their balance and perform a multisensory task, such as focussing on perceiving speech whilst walking, the activity in the brain regions associated with balance (e.g., the somatosensory cortex [121,122]) may be reduced, whilst the brain regions associated with audiovisual speech perception (e.g., superior temporal sulcus [94,123]) may be more active [25,91,120]. The requirement to process speech diverts the attentional resources required for stable balance and results in a fall, a concept which is in line with the information degradation hypothesis. The hypothesis suggests that humans possess a limited amount of attentional resources; age-related degradations of auditory inputs place demand on these resources (i.e., there is an increased effort to process auditory information). This results in the diversion of cognitive resources, away from balance and towards tasks like speech-in-noise perception, for example, which require effortful listening [12].

The role of attention in balance maintenance and fall risk has therefore regularly been investigated using dual-task methodologies, assessing the impact that manipulating the attentional demands required for different postural conditions has on perceptual performance. For example, Lajoie et al. [124] asked participants to provide a verbal response to an auditory stimulus whilst sitting, standing, and walking and found that attentional costs were greater (i.e., perceptual performance was worse) in the walking condition compared to the seated and standing conditions. The authors concluded that more challenging balance conditions required a greater allocation of attentional resources, suggesting that balance maintenance loads the cognitive system and the attentional control required may detract from integrative processes required for other tasks, such as speech perception [124].

This is supported by research by Stapleton et al. [125], who asked participants to complete the sound-induced flash illusion whilst sitting and standing; they found that fall-prone older adults were more susceptible to the illusory effects when standing than when sitting, whilst healthy older adults did not show a difference in susceptibility to the illusion across the postural conditions. Stapleton et al. [125] argued that fall-prone older adults require more attentional resources to maintain balance, leaving fewer attentional resources for the multisensory sound-induced flash task and therefore displaying increased—less modulated—integration of visual and auditory inputs that were not temporally aligned (i.e., producing more illusory percepts). As such, dual-task multisensory integration in older adults may be dependent upon how they allocate the necessary attentional resources—to the multisensory task at hand, or to maintaining balance.

In sum, the cognitive mechanisms required for audiovisual integration are strongly associated with balance maintenance and fall risk. This highlights the importance of investigating how such mechanisms are affected by healthy ageing to understand the impact of age-related changes in multisensory integration. In order to gain a truly comprehensive understanding, it is necessary to study how the neurobiological basis of multisensory integration changes as a function of ageing—relying on behavioural data alone is not likely to provide a thorough explanation as to how the central nervous system processes and combines multisensory information.

2.7. Neurobiology of Multisensory Integration

Previous research has uncovered multiple sub-cortical and cortical brain regions associated with multisensory integration, which work together to bind visual and auditory information that is temporally, spatially, and semantically congruent (see [126,127] for recent meta-analyses identifying the implicated brain areas). The following sections of this review will focus on arguably the most renowned cortical region for audiovisual integration—the superior temporal sulcus (STS; [128])—as well as discussing the neural oscillations within sensory cortices that may play a key role in the modulation of multisensory processing.

From a neurobiological perspective, the STS is a clear target for research into audiovisual integration due to its location at the junction between occipital and temporal cortex [32]. Neurons within the STS display strong activation during the processing of meaningful everyday visual and auditory stimuli, such as moving people or objects, or speech and language comprehension [78,128–132]. Activity in the STS also reflects the "super-additivity" theory in multisensory integration, in that bimodal stimuli elicit a greater neural response in this brain area than when unisensory stimuli are presented [128] (however, see [133]). Indeed, Wright et al. [132] found that whilst the posterior STS responded strongly to visual stimuli, and the anterior STS responded strongly to auditory stimuli, combined audiovisual stimuli provoked the strongest neural response throughout the STS. Crucially, brain imaging research has indicated that multisensory effects in the STS are greatest (i.e., neural activity is increased) when participants listen to speech in noise; participants use congruent visual information to support the noisy, ambiguous auditory information and subsequently facilitate speech perception [78,130,134–137].

The STS has also been implicated in specific mechanisms like the temporal binding window—researchers have presented participants with multisensory stimuli and analysed how temporal and spatial factors evoke activations in different brain areas [138–140]. For example, Calvert et al. [138] exposed participants to audiovisual stimuli in the form of a person reading a story, in which the visual and auditory inputs were either congruent or incongruent. The researchers found that the congruent condition, in which multisensory integration is quick and accurate due to the visual and auditory stimuli being temporally and semantically aligned, evoked a greater neural response in the STS compared to the incongruent condition. This is supported by research by Powers et al. [141], who not only found that perceptual training can narrow the TBW and improve the temporal precision of multisensory integration (as did [33]), but using fMRI, the researchers also found that these changes were reflected in decreased activity in the STS. The STS is therefore strongly implicated in the evaluation of the temporal factors necessary for multisensory integration.

A growing body of evidence suggests that the STS plays a key role in the susceptibility to the McGurk effect, displaying increased bilateral activation when the incongruent auditory and visual inputs are bound together in the task [142]. This is supported by a fMRI-TMS study conducted by Beauchamp et al. [143], who found that perturbing neural activity in the STS reduced the number of McGurk responses provided by participants, and this perturbation did not influence responses to non-McGurk stimuli [63,143]. Overall, the STS is clearly implicated in the binding of visual and auditory information in the dynamic, multisensory environments that people must make sense of in everyday life scenarios like speech perception [32,133,140,144,145].

However, it is important to note that when comparing neural activity in younger and older adults during a McGurk task, fMRI data from Diaz and Yalcinbas [63] revealed that each age group engaged different brain regions and thus different mechanisms throughout the task. Younger adults relied heavily on sensory cortices such as the superior temporal gyrus, whereas older adults were more likely to utilise frontal brain regions including the superior frontal gyrus (involved in executive function) and the superior parietal lobule (involved in attentional control). This indicates that older adults required more cognitive resources than younger adults to perceive audiovisual speech, once again highlighting the important role of cognitive control in multisensory processing [90]. The authors suggested, in line with previous research discussed in this review, that older adults may rely on alternative strategies to perceive audiovisual speech as a potential compensatory mechanism for declines in sensory function [7,28,48,63]. Fundamentally, these data suggest that the STS is not exclusive for its role in multisensory integration, and it is instead highly likely that multiple different sensory and cognitive brain areas are functionally connected (e.g., the superior parietal cortex, prefrontal cortex, premotor cortex; [78,127,146]), working together to bind visual and auditory inputs in younger and older adults for quick and accurate performance in tasks like speech perception and balance maintenance.

2.8. Oscillatory Alpha Activity in Multisensory Integration

Whilst the specific brain regions associated with bottom-up and top-down multisensory integration have been well-established using techniques such as fMRI and PET, arguably less is known about the neural oscillations involved in multisensory integration and how these may change with healthy ageing. Neural oscillations are a compelling area of research due to their ability to index the synchronisation of brain activity within and across cortical areas, providing crucial insight into the neurophysiology of perception and cognition [147]. Due to the fact that multisensory integration engages multiple different brain regions, oscillatory activity can reveal how these areas coordinate with each other to facilitate perception. Specifically, oscillations reflect neural activity on a population level [148], providing a direct indication of the brain areas that simultaneously exhibit increased activation during the processing and binding of audiovisual information. Using neural oscillations, it is therefore possible to examine, with high temporal accuracy, the activity and functional connectivity in different brain regions during multisensory integration [149] and how this may change with healthy ageing. In addition, in the same way that we can link different brain regions like the STS to certain functions, oscillations in different frequency bands (alpha, beta, gamma, and theta) are believed to be responsible for specific mechanisms; bottom-up sensory processing is often associated with gamma-band activity (greater than 30 Hz), whereas top-down modulation of sensory processing is linked to lower frequency bands (less than 30 Hz) [149,150]. Studying simultaneous fluctuations in oscillatory activity within these frequency bands during behavioural tasks allows conclusions to be drawn regarding their roles in perception, cognition, and action [149]. An area of research which is generating increasing interest is the link between attentional control, multisensory integration, and cortical oscillations in the alpha band (8 Hz–12 Hz). Historically, alpha oscillations have often been referred to as “idling” rhythms, indicative of resting brain areas. However, oscillatory alpha activity is also strongly associated with the top-down processes involved in multisensory integration such as selective attention [151,152].

Increases in alpha activity, particularly in parieto-occipital regions, are believed to reflect the effort required to suppress distracting, task-irrelevant sensory information [151–157]; likewise, decreases in alpha power are indicative of increased neural activation in sensory brain regions, facilitating sensory processing [152,158,159]. When participants are directed towards an area of space in which the target stimulus is presented, alpha power decreases in parieto-occipital regions contralateral to the attended location [160,161] and increases in ipsilateral parieto-occipital brain regions [151,158,162,163]. In this way, attentional cuing tasks akin to those used by Posner et al. [164] have been implemented with unisensory and multisensory stimuli, comparing alpha power in the "attending" hemisphere to alpha power in the "ignoring" hemisphere during the task to analyse the participant's ability to inhibit task-irrelevant information [111,152]. Taken together, this highlights alpha-band oscillations as a clear target for analysis of neural activity during multisensory processing under different attentional conditions.

Crucially, due to the hypothesised role of alpha in selective attention, and the deterioration of inhibitory abilities with healthy ageing, it is fair to suggest that younger and older adults may display age-related differences in alpha activity [102,103,107,108]. Borghini et al. [108] designed a transcranial alternating current stimulation (tACS) experiment to causally link age-related changes in alpha oscillations to inhibitory performance during a working memory task that required participants to ignore task-irrelevant information. Not only did the researchers confirm previous findings that inhibitory abilities were weaker in older adults, but also, Borghini et al. [108] found that stimulating alpha-band activity in the parietal region of older adults improved their inhibitory performance, to the extent that they were equally successful in the task as younger adults. These important findings indicate a clear link between alpha oscillations and inhibitory control; an age-related reduction in alpha activity in older adults may result in their weaker ability to ignore task-irrelevant information. Stimulation increased alpha activity and older adults subsequently displayed improvements in inhibitory control [108]. The findings of Borghini et al. [108] are a positive indication that whilst alpha activity and inhibitory abilities may diminish as we age, they could indeed be modulated through brain stimulation.

The role of oscillatory alpha power has also been studied in relation to speech perception in noisy environments. For example, O'Sullivan et al. [165] analysed participants' alpha activity under cocktail-party conditions [98] and manipulated whether audiovisual inputs were congruent or incongruent; they found that alpha activity over the parieto-occipital brain regions could indicate whether the participant was attending to the visual modality or the auditory modality. That is, when successful performance in the task required participants to ignore incongruent visual information, EEG data displayed increases in alpha activity over parieto-occipital electrodes. In addition, in the condition where visual and auditory information was congruent, alpha activity decreased—both sensory modalities were receiving task-relevant information that facilitated speech processing, there was no distracting sensory input and therefore alpha activity was lower [152,165].

Recent research has therefore investigated whether the weaker performance of older adults in speech-in-noise tasks may be reflected in age-related differences in alpha power. For example, Tune et al. [166] asked middle-aged and older adults to complete a dichotic listening task in a noisy acoustic environment. Interestingly, the researchers found that on a neural level, middle-aged and older adults showed a similar modulation of alpha power, and on a behavioural level, both age groups performed similarly in the task [166]. Contrary to evidence suggesting that older adults may have inhibitory deficits, these findings suggest that selective spatial attention may be preserved with healthy ageing [166,167]. Tune et al. [166] also highlighted the high level of variability between participants when measuring data as sensitive as alpha power, finding that other cognitive characteristics of participants, such as education and working memory, were stronger predictors of behavioural performance than age. Indeed, Stern et al. [168] explained the importance of lifestyle and experiences in the ability to compensate for age-related declines in cognitive processes like attention. Namely, engaging in more social activities or education throughout our lives, for example, accumulates cognitive "reserve", a resource bank which allows for the use of alternative cognitive strategies and which strengthens existing brain networks (see [68] for a detailed review). Individual differences in cognitive reserve would result in a mixed performance between younger and older adults in tasks that require inhibitory processes and attentional control, like speech-in-noise tasks. This once again highlights the importance of accounting for the sensory and cognitive individual differences of participants in multisensory research, especially when studying the sensitive age-related changes in such processes [28,44].

There is also evidence suggesting that the alpha band is strongly associated with temporal elements of multisensory processing, researched through the implementation of some of the illusions discussed earlier in this review. Crucially, Klimesch et al. [157] argued that alpha oscillations are responsible for the creation of time ranges in which sensory processing can occur, reflective of the concept of the TBW. This is supported by theories posited by Jensen and Mazaheri [169] and Ruhnau et al. [170]; oscillatory alpha may control the temporal processing of sensory information by establishing the temporal boundaries in which processing can occur after stimulus presentation. In other words, some researchers have suggested that the length of the oscillatory cycle directly relates to the TBW for multisensory integration, in which individual alpha frequency could predict the susceptibility to audiovisual illusory percepts. For example, Cecere et al. [171] hypothesised that the duration of an alpha oscillation could index the temporal window for the integration of visual and auditory information in the sound-induced flash illusion. The researchers found a positive correlation between individual alpha frequency (IAF) and the TBW at which the illusion could be maximally perceived; a lower IAF produced a longer TBW for multisensory integration to occur [155], increasing the susceptibility to the illusion at longer SOAs. This finding was replicated by Keil and Senkowski [155], who implemented the same paradigm and found that the length of the individual alpha band cycle in participants' occipital cortex indexed the TBW for multisensory integration, further highlighting the important role that oscillatory alpha activity plays in audiovisual integration—both with respect to attentional control and temporal processing [151].

The critical finding, with respect to multisensory integration, is that oscillatory alpha activity appears to impact perception by modulating the excitability of the sensory cortices [151]. When cortical excitability is high (i.e., alpha power is low), neurons within that brain region are more likely to be activated resulting in increased multisensory integration.

2.9. Oscillatory Alpha Activity in Balance Maintenance and Fall Risk

As mentioned previously, balance maintenance and postural control are dependent upon the accurate integration of visual, auditory, proprioceptive and vestibular information [172]. Over recent years, it has been argued that cortical brain regions become increasingly involved in balance due to age-related declines in sub-cortical (cortico-thalamic) sensorimotor tracts and sensory deterioration [173–175]. As such, age-related changes in cortical frequency band activity are likely to uncover underlying neural reasons behind the increased risk of falls in older adults. In contrast to methods like fMRI, EEG can measure neural activity whilst participants are seated, standing, walking, or lying down, rendering it an incredibly useful technique to study how the different frequency bands contribute to balance maintenance by manipulating posture [175]. Whilst research has found that, under difficult balance conditions, there is increased activity in the theta band over parietal [176] and frontal [177] brain areas, alpha oscillations once again appear to be the cortical frequency band most highly associated with the multisensory, attentional aspects of balance.

For example, Edwards et al. [175] monitored alpha band activity whilst their sample of younger adult participants completed balance tasks of varying difficulty. As balance conditions became more challenging, the researchers found that alpha power decreased in central and parietal brain regions, reflecting the increased cortical excitability during balance maintenance [175]. The decreases in alpha power that Edwards et al. [175] found in the central and parietal brain regions during difficult balance tasks suggests that these regions were allocated increased attentional resources required for postural control, further supporting the role of alpha band activity in the attentional modulation of multisensory integration and simultaneous balance maintenance [175,178].

Paradigms have also been designed to measure differences in oscillatory alpha activity between younger adults, non-falling older adults, and older adults with a history of falls. Scurry et al. [179] implemented the sound-induced flash illusion with each of these groups; they measured oscillatory gamma activity (30–80 Hz) as an indicator of sensory processing and studied how this sensory processing is modulated by alpha activity, assessing the subsequent effect on susceptibility to the illusion. The researchers found that fall-prone older adults displayed a greater illusion strength than non-fall older adults and younger adults, which was a behavioural indication of increased multisensory integration in individuals who were at a greater risk of falls. Crucially, on a neural level, Scurry et al. [179] also found reduced phase-amplitude coupling between oscillatory alpha and gamma activity in fall-prone older adults compared to non-fall older adults and younger adults, which the researchers interpreted as a reduced top-down modulation of multisensory processing in fall-prone older adults. Taken together, it is likely that strong links exist between oscillatory alpha power and balance ability/fall risk, potentially due to the relationships both factors have with attentional control and multisensory integration. Studying more about these relationships and how they change as a function of ageing is key, with the aim of understanding how to improve the perception of and safe navigation through the dynamic everyday environment for older adults.

2.10. Concluding Remarks and Future Directions

This narrative review has highlighted current discussions emerging from research into the age-related changes in multisensory integration. Considering the fact that functions such as the temporal binding window and attentional control both appear to be susceptible to age-related declines, and both appear to have a significant influence on accurate and timely audiovisual integration, it is essential that they are not treated as mutually exclusive entities in terms of their influence on multisensory perception and how it changes across the lifespan [1,96].

The objective of this review was to provide a novel perspective on the shared mechanisms involved in audiovisual integration for speech processing and fall risk in older adults, as well as to investigate the role of oscillatory alpha activity in such mechanisms. The evidence reviewed suggests that speech perception becomes more difficult due to age-related changes in the modulation of audiovisual integration; weaker attentional control impacts older adults' ability to suppress distractors and process only the most relevant, reliable sensory information when disambiguating speech. Likewise, these same attentional deficits that potentially exist in older adults appear to impede their balance; age-related changes in the ability to efficiently allocate attentional resources may be an underlying cognitive reason behind older adults' increased risk of falls. Taken together, this review has highlighted how the top-down modulation of multisensory integration required to quickly, accurately, and safely interpret our environment may be significantly affected by healthy ageing, focussing on oscillatory alpha activity as the main neural correlate in attentional control, inhibition, and precise audiovisual integration. To our knowledge, this is the first review in which speech perception and fall risk have been considered in conjunction, to discuss the common cognitive and perceptual factors responsible for successful performance in each everyday task and how these change as a function of healthy ageing.

Using behavioural tasks such as the stream–bounce illusion or speech-in-noise paradigms, together with neuroscientific techniques like EEG, TMS, and fMRI, is a strong method for researchers to establish cause and effect associations between brain areas like the STS and the key processes required to bind auditory and visual inputs. As opposed to focussing on one single brain area in isolation, it is important that research shifts to acknowledge the numerous brain regions and frequency bands involved in multisensory integration, studying how they work together to perceive audiovisual events. The role of oscillatory alpha activity, in particular, appears to be a promising area of research due to its implication in the top-down modulation of multisensory processing; measuring neural oscillations like this allows for the investigation of how different brain areas coordinate to produce quick and accurate percepts of the environment. Analysing oscillatory activity across multiple cortical sites will provide crucial insights into how these areas are functionally connected and how this activity differs between younger and older adults. Throughout these studies, the individual differences of participants must be considered and minimised where possible, including variability in unisensory function, and in lifestyle factors like education and socialisation, which contribute to cognitive reserve. This would allow for accurate comparisons between age groups regarding how multisensory tasks like speech perception and balance maintenance are likely to develop as we age.

Given our increasingly ageing population, it is clear how important it is to research how multisensory integration changes with age and how this affects speech perception and incidence of falls, both of which have a significant impact on our quality of life [9,10]. A stronger understanding of age-related changes in multisensory integration may potentially lead to the development of cognitive treatments and therapies designed to strengthen the attentional control of older adults, improving their ability to quickly and accurately integrate relevant audiovisual information.

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References

1 Talsma, D.; Senkowski, D.; Soto-Faraco, S.; Woldorff, M.G. The multifaceted interplay between attention and multisensory integration. *Trends Cogn. Sci.* **2010**, *14*, 400–410.1.

2 Vroomen, J.; Keetels, M. Perception of intersensory synchrony: A tutorial review. *Atten. Percept. Psychophys.* **2010**, *72*, 871–884. https://doi.org/10.3758/app.72.4.871.

3 Hillock, A.R.; Powers, A.R.; Wallace, M.T. Binding of sights and sounds: Age-related changes in

multisensory temporal processing. *Neuropsychologia* **2011**, *49*, 461–467. https://doi.org/10.1016/j.neuropsychologia.2010.11.041.

4 Zampini, M.; Guest, S.; Shore, D.I.; Spence, C. Audio-visual simultaneity judgments. *Percept. Psychophys.* **2005**, *67*, 531–544. https://doi.org/10.3758/bf03193329.

5 Stevenson, R.A.; Zemtsov, R.K.; Wallace, M.T. Individual differences in the multisensory temporal binding window predict susceptibility to audiovisual illusions. *J. Exp. Psychol. Hum. Percept. Perform.* **2012**, *38*, 1517–1529. https://doi.org/10.1037/a0027339.

6 Parise, C.V.; Harrar, V.; Ernst, M.O.; Spence, C. Cross-correlation between Auditory and Visual Signals Promotes Multisensory Integration. *Multisensory Res.* **2013**, *26*, 307–316. https://doi.org/10.1163/22134808-00002417.

7 de Dieuleveult, A.L.; Siemonsma, P.C.; van Erp, J.B.F.; Brouwer, A.-M. Effects of Aging in Multisensory Integration: A Systematic Review. *Front. Aging Neurosci.* **2017**, *9*, 80. https://doi.org/10.3389/fnagi.2017.00080.

8 Higgen, F.L.; Heine, C.; Krawinkel, L.; Göschl, F.; Engel, A.K.; Hummel, F.C.; Xue, G.; Gerloff, C. Crossmodal Congruency Enhances Performance of Healthy Older Adults in Visual-Tactile Pattern Matching. *Front. Aging Neurosci.* **2020**, *12*, 74. https://doi.org/10.3389/fnagi.2020.00074.

9 Cavazzana, A.; Röhrborn, A.; Garthus-Niegel, S.; Larsson, M.; Hummel, T.; Croy, I. Sensory-specific impairment among older people. An investigation using both sensory thresholds and subjective measures across the five senses. *PLoS ONE* **2018**, *13*, e0202969. https://doi.org/10.1371/journal.pone.0202969.

10 Fischer, M.E.; Cruickshanks, K.J.; Klein, B.E.; Klein, R.; Schubert, C.R.; Wiley, T.L. Multiple sensory impairment and quality of life. *Ophthalmic Epidemiol.* **2009**, *16*, 346–353. https://doi.org/10.3109/09286580903312236.

11 Bucks, R.S.; Ashworth, D.L.; Wilcock, G.K.; Siegfried, K. Assessment of activities of daily living in dementia: Development of the Bristol Activities of Daily Living Scale. *Age Ageing* **1996**, *25*, 113–120.

12 Slade, K.; Plack, C.J.; Nuttall, H.E. The Effects of Age-Related Hearing Loss on the Brain and Cognitive Function. *Trends Neurosci.* **2020**, *43*, 810–821. https://doi.org/10.1016/j.tins.2020.07.005.

13 Weissgerber, T.; Müller, C.; Stöver, T.; Baumann, U. Age differences in speech perception in noise and sound local-ization in individuals with subjective normal hearing. *Front. Psychol.* **2022**, *13*, 845285.

14 Office for Health Improvement and Disparities. (2022, February). Falls: Applying All Our Health. Gov.uk. Available online: https://www.gov.uk/government/publications/falls-applying-all-our-health/falls-applying-all-our-health (accessed on 2 March 2022).

15 Park, H.; Nannt, J.; Kayser, C. Sensory- and memory-related drivers for altered ventriloquism effects and aftereffects in older adults. *Cortex* **2021**, *135*, 298–310. https://doi.org/10.1016/j.cortex.2020.12.001.

16 Laurienti, P.J.; Burdette, J.H.; Maldjian, J.A.; Wallace, M.T. Enhanced multisensory integration in older adults. *Neurobiol. Aging* **2006**, *27*, 1155–1163. https://doi.org/10.1016/j.neurobiolaging.2005.05.024.

17 Laurienti, P.J.; Kraft, R.A.; Maldjian, J.A.; Burdette, J.H.; Wallace, M.T. Semantic congruence is a

critical factor in multisensory behavioral performance. *Exp. Brain Res.* **2004**, *158*, 405–414. https://doi.org/10.1007/s00221-004-1913-2.

18 Jones, S.A.; Beierholm, U.; Meijer, D.; Noppeney, U. Older adults sacrifice response speed to preserve multisensory integration performance. *Neurobiol. Aging* **2019**, *84*, 148–157. https://doi.org/10.1016/j.neurobiolaging.2019.08.017.

19 Meredith, M.A.; Stein, B.E. Interactions Among Converging Sensory Inputs in the Superior Colliculus. *Science* **1983**, *221*, 389–391. https://doi.org/10.1126/science.6867718.

20 Peiffer, A.M.; Mozolic, J.L.; Hugenschmidt, C.E.; Laurienti, P.J. Age-related multisensory enhancement in a simple audiovisual detection task. *Neuroreport* **2007**, *18*, 1077–1081. https://doi.org/10.1097/wnr.0b013e3281e72ae7.

21 Mahoney, J.R.; Li, P.C.C.; Oh-Park, M.; Verghese, J.; Holtzer, R. Multisensory integration across the senses in young and old adults. *Brain Res.* **2011**, *1426*, 43–53. https://doi.org/10.1016/j.brainres.2011.09.017.

22 Liu, X.Z.; Yan, D. Ageing and hearing loss. *J. Pathol. A J. Pathol. Soc. Great Br. Irel.* **2007**, *211*, 188–197.

23 Klein, B.E.; Moss, S.E.; Klein, R.; Lee, K.E.; Cruickshanks, K.J. Associations of visual function with physical outcomes and limitations 5 years later in an older population: The Beaver Dam eye study. *Ophthalmology* **2003**, *110*, 644–650. https://doi.org/10.1016/s0161-6420(02)01935-8.

24 American Optometric Association. (n.d). Adult Vision: 41 to 60 Years of Age. Available online: https://www.aoa.org/healthy-eyes/eye-health-for-life/adult-vision-41-to-60-years-of-age?sso=y (accessed on 6 June 2022).

25 Mozolic, J.L.; Hugenschmidt, C.E.; Peiffer, A.M.; Laurienti, P.J. Multisensory integration and aging. In *The Neural Bases of Multisensory Processes*; CRC Press/Taylor & Francis: Boca Raton, FL, USA, 2012.

26 Baraldi, G.D.S.; Almeida, L.C.D.; Borges, A.C.D.C. Hearing loss in aging. *Rev. Bras. Otorrinolaringol.* **2007**, *73*, 64–70.

27 Trelle, A.N.; Henson, R.N.; Simons, J.S. Neural evidence for age-related differences in representational quality and strategic retrieval processes. *Neurobiol. Aging* **2019**, *84*, 50–60. https://doi.org/10.1016/j.neurobiolaging.2019.07.012.

28 Hirst, R.J.; Setti, A.; Kenny, R.A.; Newell, F.N. Age-related sensory decline mediates the Sound-Induced Flash Illusion: Evidence for reliability weighting models of multisensory perception. *Sci. Rep.* **2019**, *9*, 19347. https://doi.org/10.1038/s41598-019-55901-5.

29 Meredith, M.A.; Stein, B.E.; Caruso, V.C.; Pages, D.S.; Sommer, M.A.; Groh, J.M.; Krüger, H.M.; Collins, T.; Englitz, B.; Cavanagh, P.; et al. Visual, auditory, and somatosensory convergence on cells in superior colliculus results in multisensory integration. *J. Neurophysiol.* **1986**, *56*, 640–662. https://doi.org/10.1152/jn.1986.56.3.640.

30 Miller, J. Divided attention: Evidence for coactivation with redundant signals. *Cogn. Psychol.* **1982**, *14*, 247–279. https://doi.org/10.1016/0010-0285(82)90010-x.

31 Miller, J. Statistical facilitation and the redundant signals effect: What are race and coactivation models? *Attention, Perception, Psychophys.* **2016**, *78*, 516–519. https://doi.org/10.3758/s13414-015-

1017-z.

32 Wallace, M.T.; Stevenson, R.A. The construct of the multisensory temporal binding window and its dysregulation in developmental disabilities. *Neuropsychologia* **2014**, *64*, 105–123. https://doi.org/10.1016/j.neuropsychologia.2014.08.005.

33 McGovern, D.P.; Burns, S.; Hirst, R.J.; Newell, F.N. Perceptual training narrows the temporal binding window of audiovisual integration in both younger and older adults. *Neuropsychologia* **2022**, *173*, 108309. https://doi.org/10.1016/j.neuropsychologia.2022.108309.

34 Mégevand, P.; Molholm, S.; Nayak, A.; Foxe, J.J. Recalibration of the Multisensory Temporal Window of Integration Results from Changing Task Demands. *PLoS ONE* **2013**, *8*, e71608. https://doi.org/10.1371/journal.pone.0071608.

35 Pöppel, E.; Schill, K.; von Steinbüchel, N. Multistable states in intrahemispheric learning of a sensorimotor task. *Neuroreport Int. J. Rapid Commun. Res. Neurosci.* **1990**, *1*, 69–72.

36 Vatakis, A.; Spence, C. Audiovisual synchrony perception for music, speech, and object actions. *Brain Res.* **2006**, *1111*, 134–142. https://doi.org/10.1016/j.brainres.2006.05.078.

37 Vatakis, A.; Spence, C. Crossmodal binding: Evaluating the "unity assumption" using audiovisual speech stimuli. *Percept. Psychophys.* **2007**, *69*, 744–756.

38 Van Wassenhove, V.; Grant, K.W.; Poeppel, D. Temporal window of integration in auditory-visual speech perception. *Neuropsychologia* **2007**, *45*, 598–607.

39 Basharat, A.; Adams, M.S.; Staines, W.; Barnett-Cowan, M. Simultaneity and Temporal Order Judgments Are Coded Differently and Change with Age: An Event-Related Potential Study. *Front. Integr. Neurosci.* **2018**, *12*, 15. https://doi.org/10.3389/fnint.2018.00015.

40 Noel, J.-P.; De Niear, M.; Van der Burg, E.; Wallace, M.T. Audiovisual Simultaneity Judgment and Rapid Recalibration throughout the Lifespan. *PLoS ONE* **2016**, *11*, e0161698. https://doi.org/10.1371/journal.pone.0161698.

41 Bedard, G.; Barnett-Cowan, M. Impaired timing of audiovisual events in the elderly. *Exp. Brain Res.* **2016**, *234*, 331–340. https://doi.org/10.1007/s00221-015-4466-7.

42 Setti, A.; Stapleton, J.; Leahy, D.; Walsh, C.; Kenny, R.A.; Newell, F.N. Improving the efficiency of multisensory integration in older adults: Audio-visual temporal discrimination training reduces susceptibility to the sound-induced flash illusion. *Neuropsychologia* **2014**, *61*, 259–268. https://doi.org/10.1016/j.neuropsychologia.2014.06.027.

43 Diederich, A.; Colonius, H.; Schomburg, A. Assessing age-related multisensory enhancement with the time-window-of-integration model. *Neuropsychologia* **2008**, *46*, 2556–2562. https://doi.org/10.1016/j.neuropsychologia.2008.03.026.

44 Brooks, C.J.; Chan, Y.M.; Anderson, A.J.; McKendrick, A.M. Audiovisual Temporal Perception in Aging: The Role of Multisensory Integration and Age-Related Sensory Loss. *Front. Hum. Neurosci.* **2018**, *12*, 192. https://doi.org/10.3389/fnhum.2018.00192.

45 Shams, L.; Ma, W.J.; Beierholm, U. Sound-induced flash illusion as an optimal percept. *Neuroreport* **2005**, *16*, 1923–1927. https://doi.org/10.1097/01.wnr.0000187634.68504.bb.

46 Setti, A.; Burke, K.E.; Kenny, R.A.; Newell, F.N. Is inefficient multisensory processing associated with falls in older people? *Exp. Brain Res.* **2011**, *209*, 375–384. https://doi.org/10.1007/s00221-011-2560-

z.

47 DeLoss, D.J.; Pierce, R.S.; Andersen, G.J. Multisensory integration, aging, and the sound-induced flash illusion. *Psychol. Aging,* **2013**, *28*, 802–812. https://doi.org/10.1037/a0033289.

48 de Boer-Schellekens, L.; Vroomen, J. Multisensory integration compensates loss of sensitivity of visual temporal order in the elderly. *Exp. Brain Res.* **2014**, *232*, 253–262.

49 Parker, J.L.; Robinson, C.W. Changes in multisensory integration across the life span. *Psychol. Aging* **2018**, *33*, 545–558. https://doi.org/10.1037/pag0000244.

50 Basharat, A.; Mahoney, J.R.; Barnett-Cowan, M. Temporal Metrics of Multisensory Processing Change in the Elderly. *Multisen- sory Res.* **2019**, *32*, 715–744. https://doi.org/10.1163/22134808-20191458.

51 Matsuno, T.; Tomonaga, M. Stream/bounce perception and the effect of depth cues in chimpanzees (*Pan troglodytes*). *Atten. Percept. Psychophys.* **2011**, *73*, 1532–1545. https://doi.org/10.3758/s13414-011-0126-6.

52 Sekuler, R.; Sekuler, A.B.; Lau, R. Sound alters visual motion perception. *Nature* **1997**,*385*,308–308. https://doi.org/10.1038/385308a0.

53 Donohue, S.E.; Green, J.J.; Woldorff, M.G. The effects of attention on the temporal integration of multisensory stimuli. *Front. Integr. Neurosci.* **2015**, *9*, 32. https://doi.org/10.3389/fnint.2015.00032.

54 Watanabe, K.; Shimojo, S. When Sound Affects Vision: Effects of Auditory Grouping on Visual Motion Perception. *Psychol. Sci.* **2001**, *12,* 109–116. https://doi.org/10.1111/1467-9280.00319.

55 Bushara, K.O.; Hanakawa, T.; Immisch, I.; Toma, K.; Kansaku, K.; Hallett, M. Neural correlates of cross-modal binding. *Nat. Neurosci.* **2003**, *6*, 190–195. https://doi.org/10.1038/nn993.

56 Maniglia, M.; Grassi, M.; Casco, C.; Campana, G. The origin of the audiovisual bounce inducing effect: A TMS study. *Neuropsychologia* **2012**, *50*, 1478–1482. https://doi.org/10.1016/j.neuropsychologia.2012.02.033.

57 Mcgurk, H.; Macdonald, J. Hearing lips and seeing voices. *Nature* **1976**, *264*, 746–748. https://doi.org/10.1038/264746a0.

58 Kraus, N.; Slater, J. Music and language: Relations and disconnections. *Handb. Clin. Neurol.* **2015**, *129*, 207–222.

59 Sekiyama, K.; Soshi, T.; Sakamoto, S. Enhanced audiovisual integration with aging in speech perception: A heightened McGurk effect in older adults. *Front. Psychol.* **2014**, *5*, 323.

60 Setti, A.; Burke, K.E.; Kenny, R.; Newell, F.N. Susceptibility to a multisensory speech illusion in older persons is driven by perceptual processes. *Front. Psychol.* **2013**, *4*, 575. https://doi.org/10.3389/fpsyg.2013.00575.

61 Thompson, L.A.; Malloy, D. Attention Resources and Visible Speech Encoding in Older and Younger Adults. *Exp. Aging Res.* **2004**, *30*, 241–252. https://doi.org/10.1080/03610730490447877.

62 Massaro, D.W. *Perceiving Talking Faces: From Speech Perception to a Behavioral Principle*; Mit Press: Cambridge, MA, USA, 1998.

63 Diaz, M.T.; Yalcinbas, E. The neural bases of multimodal sensory integration in older adults. *Int. J. Behav. Dev.* **2021**, *45*, 409–417. https://doi.org/10.1177/0165025420979362.

64 Campbell, J.; Sharma, A. Frontal Cortical Modulation of Temporal Visual Cross-Modal Re-organization in Adults with Hearing Loss. *Brain Sci.* **2020**, *10*, 498. https://doi.org/10.3390/brainsci10080498.

65 Glick, H.; Sharma, A. Cross-modal plasticity in developmental and age-related hearing loss: Clinical implications. *Hear. Res.* **2017**, *343*, 191–201. https://doi.org/10.1016/j.heares.2016.08.012.

66 Bavelier, D.; Hirshorn, E.A. I see where you're hearing: How cross-modal plasticity may exploit homologous brain structures. *Nat. Neurosci.* **2010**, *13*, 1309–1311. https://doi.org/10.1038/nn1110-1309.

67 Stropahl, M.; Debener, S. Auditory cross-modal reorganization in cochlear implant users indicates audio-visual integration. *NeuroImage Clin.* **2017**, *16*, 514–523.

68 Oosterhuis, E.J.; Slade, K.; May, P.J.C.; Nuttall, H.E. Toward an Understanding of Healthy Cognitive Aging: The Importance of Lifestyle in Cognitive Reserve and the Scaffolding Theory of Aging and Cognition. *J. Gerontol. Ser. B* **2023**, *78*, 777–788. https://doi.org/10.1093/geronb/gbac197.

69 Puschmann, S.; Daeglau, M.; Stropahl, M.; Mirkovic, B.; Rosemann, S.; Thiel, C.M.; Debener, S. Hearing-impaired listeners show increased audiovisual benefit when listening to speech in noise. *NeuroImage* **2019**, *196*, 261–268. https://doi.org/10.1016/j.neuroimage.2019.04.017.

70 Rosemann, S.; Thiel, C.M. Audio-visual speech processing in age-related hearing loss: Stronger integration and increased frontal lobe recruitment. *NeuroImage* **2018**, *175*, 425–437.

71 Basu Mallick, D.; FMagnotti, J.; SBeauchamp, M. Variability and stability in the McGurk effect: Contributions of participants, stimuli, time, and response type. *Psychon. Bull. Rev.* **2015**, *22*, 1299–1307.

72 Dully, J.; McGovern, D.P.; O'connell, R.G. The impact of natural aging on computational and neural indices of perceptual decision making: A review. *Behav. Brain Res.* **2018**, *355*, 48–55. https://doi.org/10.1016/j.bbr.2018.02.001.

73 Sommers, M.S.; Tye-Murray, N.; Spehar, B. Auditory-Visual Speech Perception and Auditory-Visual Enhancement in Normal- Hearing Younger and Older Adults. *Ear Hear.* **2005**, *26*, 263–275. https://doi.org/10.1097/00003446-200506000-00003.

74 Van Engen, K.J.; Dey, A.; Sommers, M.S.; Peelle, J.E. Audiovisual speech perception: Moving beyond McGurk. *J. Acoust. Soc. Am.* **2022**, *152*, 3216–3225. https://doi.org/10.1121/10.0015262.

75 Alsius, A.; Paré, M.; Munhall, K.G. Forty Years After Hearing Lips and Seeing Voices: The McGurk Effect Revisited. *Multisensory Res.* **2018**, *31*, 111–144. https://doi.org/10.1163/22134808-00002565.

76 Getz, L.M.; Toscano, J.C. Rethinking the McGurk effect as a perceptual illusion. *Atten. Percept. Psychophys.* **2021**, *83*, 2583–2598. https://doi.org/10.3758/s13414-021-02265-6.

77 Massaro, D.W. The McGurk effect: Auditory visual speech perception's piltdown man. In Proceedings of the 14th International Conference on Auditory-Visual Speech Processing 2017, Stockholm, Sweden, 25–26 August 2017.

78 Peelle, J.E.; Spehar, B.; Jones, M.S.; McConkey, S.; Myerson, J.; Hale, S.; Sommers, M.S.; Tye-Murray, N. Increased Connectivity among Sensory and Motor Regions during Visual and Audiovisual Speech Perception. *J. Neurosci.* **2022**, *42*, 435–442. https://doi.org/10.1523/jneurosci.0114-21.2021.

79 Tye-Murray, N.; Spehar, B.; Myerson, J.; Hale, S.; Sommers, M. Lipreading and audiovisual speech recognition across the adult lifespan: Implications for audiovisual integration. *Psychol. Aging* **2016**, *31*, 380–389. https://doi.org/10.1037/pag0000094.

80 Begau, A.; Klatt, L.I.; Schneider, D.; Wascher, E.; Getzmann, S. The role of informational content of visual speech in an audiovisual cocktail party: Evidence from cortical oscillations in young and old participants. *Eur. J. Neurosci.* **2022**, *56*, 5215–5234.

81 van Wassenhove, V.; Grant, K.W.; Poeppel, D. Visual speech speeds up the neural processing of auditory speech. *Proc. Natl. Acad. Sci. USA* **2005**, *102*, 1181–1186. https://doi.org/10.1073/pnas.0408949102.

82 Stevenson, R.A.; Nelms, C.E.; Baum, S.H.; Zurkovsky, L.; Barense, M.D.; Newhouse, P.A.; Wallace, M.T. Deficits in audiovisual speech perception in normal aging emerge at the level of whole-word recognition. *Neurobiol. Aging* **2015**, *36*, 283–291. https://doi.org/10.1016/j.neurobiolaging.2014.08.003.

83 Winneke, A.H.; Phillips, N.A. Does audiovisual speech offer a fountain of youth for old ears? An event-related brain potential study of age differences in audiovisual speech perception. *Psychol. Aging* **2011**, *26*, 427–438. https://doi.org/10.1037/a0021683.

84 Begau, A.; Klatt, L.I.; Wascher, E.; Schneider, D.; Getzmann, S. Do congruent lip movements facilitate speech pro-cessing in a dynamic audiovisual multi-talker scenario? An ERP study with older and younger adults. *Behav. Brain Res.* **2021**, *412*, 113436.

85 Tye-Murray, N.; Sommers, M.; Spehar, B.; Myerson, J.; Hale, S. Aging, Audiovisual Integration, and the Principle of Inverse Effectiveness. *Ear Hear.* **2010**, *31*, 636–644. https://doi.org/10.1097/aud.0b013e3181ddf7ff.

86 Gordon, M.S.; Allen, S. Audiovisual Speech in Older and Younger Adults: Integrating a Distorted Visual Signal With Speech in Noise. *Exp. Aging Res.* **2009**, *35*, 202–219. https://doi.org/10.1080/03610730902720398.

87 Dey, A.; Sommers, M.S. Age-related differences in inhibitory control predict audiovisual speech perception. *Psychol. Aging* **2015**, *30*, 634–646. https://doi.org/10.1037/pag0000033.

88 Sommers, M.S.; Spehar, B.; Tye-Murray, N.; Myerson, J.; Hale, S. Age Differences in the Effects of Speaking Rate on Auditory, Visual, and Auditory-Visual Speech Perception. *Ear Hear.* **2020**, *41*, 549–560. https://doi.org/10.1097/aud.0000000000000776.

89 Mahoney, J.R.; Cotton, K.; Verghese, J. Multisensory Integration Predicts Balance and Falls in Older Adults. *J. Gerontol. Ser. A* **2019**, *74*, 1429–1435. https://doi.org/10.1093/gerona/gly245.

90 Hirst, R.J.; Setti, A.; De Looze, C.; Kenny, R.A.; Newell, F.N. Multisensory integration precision is associated with better cognitive performance over time in older adults: A large-scale exploratory study. *Aging Brain* **2022**, *2*, 100038. https://doi.org/10.1016/j.nbas.2022.100038.

91 Mozolic, J.L.; Hugenschmidt, C.E.; Peiffer, A.M.; Laurienti, P.J. Modality-specific selective attention attenuates multisensory integration. *Exp. Brain Res.* **2008**, *184*, 39–52, https://doi.org/10.1007/s00221-007-1080-3.

92 Posner, M.I.; Driver, J. The neurobiology of selective attention. *Curr. Opin. Neurobiol.* **1992**, *2*, 165–169, https://doi.org/10.1016/0959-4388(92)90006-7.

93 Talsma, D.; Doty, T.J.; Woldorff, M.G. Selective Attention and Audiovisual Integration: Is Attending to Both Modalities a Prerequisite for Early Integration? *Cereb. Cortex* **2006**, *17*, 679–690. https://doi.org/10.1093/cercor/bhk016.

94 Fairhall, S.L.; Macaluso, E. Spatial attention can modulate audiovisual integration at multiple cortical and subcortical sites. *Eur. J. Neurosci.* **2009**, *29*, 1247–1257. https://doi.org/10.1111/j.1460-9568.2009.06688.x.

95 Roberts, K.L.; Allen, H.A. Perception and Cognition in the Ageing Brain: A Brief Review of the Short- and Long-Term Links between Perceptual and Cognitive Decline. *Front. Aging Neurosci.* **2016**, *8*, 39. https://doi.org/10.3389/fnagi.2016.00039.

96 Talsma, D. Predictive coding and multisensory integration: An attentional account of the multisensory mind. *Front. Integr. Neurosci.* **2015**, *9*, 19. https://doi.org/10.3389/fnint.2015.00019.

97 Campbell, J.; Nielsen, M.; LaBrec, A.; Bean, C. Sensory Inhibition Is Related to Variable Speech Perception in Noise in Adults With Normal Hearing. *J. Speech Lang. Hear. Res.* **2020**, *63*, 1595–1607. https://doi.org/10.1044/2020_jslhr-19-00261.

98 Cherry, E.C. Some experiments on the recognition of speech, with one and with two ears. *J. Acoust. Soc. Am.* **1953**, *25*, 975–979.

99 Schneider, B.A.; Pichora-Fuller, K.; Daneman, M. Effects of Senescent Changes in Audition and Cognition on Spoken Language Comprehension. In *The Aging Auditory System*; Springer: Berlin/Heidelberg, Germany, 2010; pp. 167–210. https://doi.org/10.1007/978-1-4419-0993-0_7.

100 Getzmann, S.; Golob, E.J.; Wascher, E. Focused and divided attention in a simulated cocktail-party situation: ERP evidence from younger and older adults. *Neurobiol. Aging* **2016**, *41*, 138–149. https://doi.org/10.1016/j.neurobiolaging.2016.02.018.

101 Fabiani, M.; Low, K.A.; Wee, E.; Sable, J.J.; Gratton, G. Reduced Suppression or Labile Memory? Mechanisms of Inefficient Filtering of Irrelevant Information in Older Adults. *J. Cogn. Neurosci.* **2006**, *18*, 637–650. https://doi.org/10.1162/jocn.2006.18.4.637.

102 Gazzaley, A.; Cooney, J.W.; McEvoy, K.; Knight, R.T.; D’Esposito, M. Top-down Enhancement and Suppression of the Magnitude and Speed of Neural Activity. *J. Cogn. Neurosci.* **2005**, *17*, 507–517. https://doi.org/10.1162/0898929053279522.

103 Gazzaley, A.; Clapp, W.; Kelley, J.; McEvoy, K.; Knight, R.T.; D’Esposito, M. Age-related top-down suppression deficit in the early stages of cortical visual memory processing. *Proc. Natl. Acad. Sci. USA* **2008**, *105*, 13122–13126. https://doi.org/10.1073/pnas.0806074105.

104 Stothart, G.; Kazanina, N. Auditory perception in the aging brain: The role of inhibition and facilitation in early processing. *Neurobiol. Aging* **2016**, *47*, 23–34. https://doi.org/10.1016/j.neurobiolaging.2016.06.022.

105 Alain, C.; Woods, D.L. Age-related changes in processing auditory stimuli during visual attention: Evidence for deficits in inhibitory control and sensory memory. *Psychol. Aging* **1999**, *14*, 507.

106 Wild-Wall, N.; Falkenstein, M. Age-dependent impairment of auditory processing under spatially focused and divided attention: An electrophysiological study. *Biol. Psychol.* **2010**, *83*, 27–36. https://doi.org/10.1016/j.biopsycho.2009.09.011.

107 Hasher, L.; Lustig, C.; Zacks, R. Inhibitory Mechanisms and the Control of Attention. *Var. Work. Mem.* **2007**, *19*, 227–249. https://doi.org/10.1093/acprof:oso/9780195168648.003.0009.

108 Borghini, G.; Candini, M.; Filannino, C.; Hussain, M.; Walsh, V.; Romei, V.; Zokaei, N.; Cappelletti, M. Alpha Oscillations Are Causally Linked to Inhibitory Abilities in Ageing. *J. Neurosci.* **2018**, *38*,

4418–4429. https://doi.org/10.1523/jneurosci.1285-17.2018.

109 Hasher, L.; Zacks, R.T. Working memory, comprehension, and aging: A review and a new view. *Psychol. Learn. Motiv.* **1988**, *22*, 193–225.

110 Pichora-Fuller, M.K.; Alain, C.; Schneider, B.A. Older adults at the cocktail party. In *The Auditory System at the Cocktail Party*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 227–259.

111 Getzmann, S.; Klatt, L.I.; Schneider, D.; Begau, A.; Wascher, E. EEG correlates of spatial shifts of attention in a dynamic multitalker speech perception scenario in younger and older adults. *Hear. Res.* **2020**, *398*, 108077.

112 Hugenschmidt, C.E.; Mozolic, J.L.; Laurienti, P.J. Suppression of multisensory integration by modality-specific attention in aging. *Neuroreport* **2009**, *20*, 349–353. https://doi.org/10.1097/wnr.0b013e328323ab07.

113 Guerreiro, M.J.S.; Anguera, J.A.; Mishra, J.; Van Gerven, P.W.M.; Gazzaley, A. Age-equivalent Top–Down Modulation during Cross-modal Selective Attention. *J. Cogn. Neurosci.* **2014**, *26*, 2827–2839. https://doi.org/10.1162/jocn_a_00685.

114 Guerreiro, M.J.S.; Adam, J.J.; Van Gerven, P.W.M. Aging and response interference across sensory modalities. *Psychon. Bull. Rev.* **2014**, *21,* 836–842. https://doi.org/10.3758/s13423-013-0554-5.

115 Guerreiro, M.J.; Eck, J.; Moerel, M.; Evers, E.A.; Van Gerven, P.W. Top-down modulation of visual and auditory cortical processing in aging. *Behav. Brain Res.* **2015**, *278*, 226–234. https://doi.org/10.1016/j.bbr.2014.09.049.

116 Lim, S.K.; Kong, S. Prevalence, physical characteristics, and fall risk in older adults with and without possible sarcopenia. *Aging Clin. Exp. Res.* **2022**, *34*, 1365–1371.

117 Callis, N. Falls prevention: Identification of predictive fall risk factors. *Appl. Nurs. Res.* **2016**, *29*, 53–58. https://doi.org/10.1016/j.apnr.2015.05.007.

118 Reed-Jones, R.J.; Solis, G.R.; Lawson, K.A.; Loya, A.M.; Cude-Islas, D.; Berger, C.S. Vision and falls: A multidisciplinary review of the contributions of visual impairment to falls among older adults. *Maturitas* **2013**, *75*, 22–28.

119 Campos, J.; Ramkhalawansingh, R.; Pichora-Fuller, M.K. Hearing, self-motion perception, mobility, and aging. *Hear. Res.* **2018**, *369*, 42–55.

120 Zhang, S.; Xu, W.; Zhu, Y.; Tian, E.; Kong, W. Impaired Multisensory Integration Predisposes the Elderly People to Fall: A Systematic Review. *Front. Neurosci.* **2020**, *14*, 411. https://doi.org/10.3389/fnins.2020.00411.

121 Hupfeld, K.; McGregor, H.; Hass, C.; Pasternak, O.; Seidler, R. Sensory system-specific associations between brain structure and balance. *Neurobiol. Aging* **2022**, *119*, 102–116. https://doi.org/10.1016/j.neurobiolaging.2022.07.013.

122 Osoba, M.Y.; Rao, A.K.; Agrawal, S.K.; Lalwani, A.K. Balance and gait in the elderly: A contemporary review. *Laryngoscope Investig. Otolaryngol.* **2019**, *4*, 143–153. https://doi.org/10.1002/lio2.252.

123 Hickok, G.; Rogalsky, C.; Matchin, W.; Basilakos, A.; Cai, J.; Pillay, S.; Ferrill, M.; Mickelsen, S.; Anderson, S.; Love, T.; et al. Neural networks supporting audiovisual integration for speech: A large-scale lesion study. *Cortex* **2018**, *103*, 360–371. https://doi.org/10.1016/j.cortex.2018.03.030.

124 Lajoie, Y.; Teasdale, N.; Bard, C.; Fleury, M. Attentional demands for static and dynamic equilibrium. *Exp. Brain Res.* **1993**, *97*, 139–144. https://doi.org/10.1007/bf00228824.

125 Stapleton, J.; Setti, A.; Doheny, E.P.; Kenny, R.A.; Newell, F.N. A standing posture is associated with increased susceptibility to the sound-induced flash illusion in fall-prone older adults. *Exp. Brain Res.* **2014**, *232*, 423–434. https://doi.org/10.1007/s00221-013-3750-7.

126 Scheliga, S.; Kellermann, T.; Lampert, A.; Rolke, R.; Spehr, M.; Habel, U. Neural correlates of multisensory integration in the human brain: An ALE meta-analysis. *Rev. Neurosci.* **2023**, *34*, 223–245. https://doi.org/10.1515/revneuro-2022-0065.

127 Gao, C.; Green, J.J.; Yang, X.; Oh, S.; Kim, J.; Shinkareva, S.V. Audiovisual integration in the human brain: A coordinate-based meta-analysis. *Cereb. Cortex* **2023**, *33*, 5574–5584.

128 Beauchamp, M.S. See me, hear me, touch me: Multisensory integration in lateral occipital-temporal cortex. *Curr. Opin. Neurobiol.* **2005**, *15*, 145–153. https://doi.org/10.1016/j.conb.2005.03.011.

129 Straube, B.; Wroblewski, A.; Jansen, A.; He, Y. The connectivity signature of co-speech gesture integration: The superior temporal sulcus modulates connectivity between areas related to visual gesture and auditory speech processing. *NeuroImage* **2018**, *181*, 539–549.

130 Rennig, J.; Beauchamp, M.S. Intelligibility of audiovisual sentences drives multivoxel response patterns in human superior temporal cortex. *NeuroImage* **2022**, *247*, 118796–118796. https://doi.org/10.1016/j.neuroimage.2021.118796.

131 Beauchamp, M.S.; Lee, K.E.; Haxby, J.V.; Martin, A. Parallel Visual Motion Processing Streams for Manipulable Objects and Human Movements. *Neuron* **2002**, *34*, 149–159. https://doi.org/10.1016/s0896-6273(02)00642-6.

132 Wright, T.M.; Pelphrey, K.A.; Allison, T.; McKeown, M.; McCarthy, G. Polysensory Interactions along Lateral Temporal Regions Evoked by Audiovisual Speech. *Cereb. Cortex* **2003**, *13*, 1034–1043. https://doi.org/10.1093/cercor/13.10.1034.

133 Ross, L.A.; Molholm, S.; Butler, J.S.; Del Bene, V.A.; Foxe, J.J. Neural correlates of multisensory enhancement in audiovisual narrative speech perception: A fMRI investigation. *NeuroImage* **2022**, *263*, 119598. https://doi.org/10.1016/j.neuroimage.2022.119598.

134 Callan, D.E.; Jones, J.A.; Munhall, K.; Callan, A.M.; Kroos, C.; Vatikiotis-Bateson, E. Neural processes underlying perceptual enhancement by visual speech gestures. *Neuroreport* **2003**, *14*, 2213–2218. https://doi.org/10.1097/00001756-200312020-00016.

135 Sekiyama, K.; Kanno, I.; Miura, S.; Sugita, Y. Auditory-visual speech perception examined by fMRI and PET. *Neurosci. Res.* **2003**, *47*, 277–287. https://doi.org/10.1016/s0168-0102(03)00214-1.

136 Amedi, A.; Von Kriegstein, K.; van Atteveldt, N.; Beauchamp, M.S.; Naumer, M.J. Functional imaging of human crossmodal identification and object recognition. *Exp. Brain Res.* **2005**, *166*, 559–571. https://doi.org/10.1007/s00221-005-2396-5.

137 Miceli, G.; Bartolomeo, P.; Navarro, V. Cross-modal integration and plasticity in the superior temporal cortex. *Handb. Clin. Neurol.* **2022**, *187*, 127–143.

138 Calvert, G.A.; Campbell, R.; Brammer, M.J. Evidence from functional magnetic resonance imaging of crossmodal binding in the human heteromodal cortex. *Curr. Biol.* **2000**, *10*, 649–657. https://doi.org/10.1016/s0960-9822(00)00513-3.

139 Bushara, K.O.; Grafman, J.; Hallett, M. Neural Correlates of Auditory–Visual Stimulus Onset Asynchrony Detection. *J. Neurosci.* **2001**, *21*, 300–304. https://doi.org/10.1523/jneurosci.21-01-00300.2001.

140 Johnston, P.R.; Alain, C.; McIntosh, A.R. Individual Differences in Multisensory Processing Are Related to Broad Differences in the Balance of Local versus Distributed Information. *J. Cogn. Neurosci.* **2022**, *34*, 846–863. https://doi.org/10.1162/jocn_a_01835.

141 Powers, A.R.; Hevey, M.A.; Wallace, M.T. Neural Correlates of Multisensory Perceptual Learning. *J. Neurosci.* **2012**, *32*, 6263– 6274. https://doi.org/10.1523/jneurosci.6138-11.2012.

142 Szycik, G.R.; Stadler, J.; Tempelmann, C.; Münte, T.F. Examining the McGurk illusion using high-field 7 Tesla functional MRI. *Front. Hum. Neurosci.* **2012**, *6*, 95. https://doi.org/10.3389/fnhum.2012.00095.

143 Beauchamp, M.S.; Nath, A.R.; Pasalar, S. fMRI-guided transcranial magnetic stimulation reveals that the superior temporal sulcus is a cortical locus of the McGurk effect. *J. Neurosci.* **2010**, *30*, 2414–2417. https://doi.org/10.1523/jneurosci. 4865-09.2010.

144 Stevenson, R.A.; Altieri, N.A.; Kim, S.; Pisoni, D.B.; James, T.W. Neural processing of asynchronous audiovisual speech perception. *NeuroImage* **2010**, *49*, 3308–3318. https://doi.org/10.1016/j.neuroimage.2009.12.001.

145 Stevenson, R.A.; VanDerKlok, R.M.; Pisoni, D.B.; James, T.W. Discrete neural substrates underlie complementary audiovisual speech integration processes. *NeuroImage* **2011**, *55*, 1339–1345. https://doi.org/10.1016/j.neuroimage.2010.12.063.

146 Tóth, B.; Farkas, D.; Urbán, G.; Szalárdy, O.; Orosz, G.; Hunyadi, L.; Hajdu, B.; Kovács, A.; Szabó, B.T.; Shestopalova, L.B.; et al. Attention and speech-processing related functional brain networks activated in a multi-speaker environment. *PLoS ONE* **2019**, *14*, e0212754. https://doi.org/10.1371/journal.pone.0212754.

147 Donoghue, T.; Schaworonkow, N.; Voytek, B. Methodological considerations for studying neural oscillations. *Eur. J. Neurosci.* **2022**, *55*, 3502–3527.

148 Wang, X.-J.; Lee, J.J.; Schmit, B.D.; Bellet, J.; Chen, C.-Y.; Hafed, Z.M.; Hoseini, M.S.; Pobst, J.; Clawson, W.; Shew, W.; et al. Neurophysiological and Computational Principles of Cortical Rhythms in Cognition. *Physiol. Rev.* **2010**, *90*, 1195–1268. https://doi.org/10.1152/physrev.00035.2008.

149 Keil, J.; Senkowski, D. Neural Oscillations Orchestrate Multisensory Processing. *Neurosci.* **2018**, *24*, 609–626. https://doi.org/10.1177/1073858418755352.

150 Siegel, M.; Donner, T.H.; Engel, A.K. Spectral fingerprints of large-scale neuronal interactions. *Nat. Rev. Neurosci.* **2012**, *13*, 121–134. https://doi.org/10.1038/nrn3137.

151 Lange, J.; Keil, J.; Schnitzler, A.; van Dijk, H.; Weisz, N. The role of alpha oscillations for illusory perception. *Behav. Brain Res.* **2014**, *271*, 294–301. https://doi.org/10.1016/j.bbr.2014.06.015.

152 Kelly, S.P.; Lalor, E.C.; Reilly, R.B.; Foxe, J.J. Increases in Alpha Oscillatory Power Reflect an Active Retinotopic Mechanism for Distracter Suppression During Sustained Visuospatial Attention. *J. Neurophysiol.* **2006**, *95*, 3844–3851. https://doi.org/10.1152/jn.01234.2005.

153 Keller, A.S.; Payne, L.; Sekuler, R. Characterizing the roles of alpha and theta oscillations in multisensory attention. *Neuropsychologia* **2017**, *99*, 48–63. https://doi.org/10.1016/j.neuropsychologia.2017.02.021.

154 Romei, V.; Gross, J.; Thut, G. On the Role of Prestimulus Alpha Rhythms over Occipito-Parietal Areas in Visual Input Regulation: Correlation or Causation? *J. Neurosci.* **2010**, *30*, 8692–8697. https://doi.org/10.1523/jneurosci.0160-10.2010.

155 Keil, J.; Senkowski, D. Individual Alpha Frequency Relates to the Sound-Induced Flash Illusion. *Multisensory Res.* **2017**, *30*, 565– 578. https://doi.org/10.1163/22134808-00002572.

156 Foxe, J.J.; Snyder, A.C. The Role of Alpha-Band Brain Oscillations as a Sensory Suppression Mechanism during Selective Attention. *Front. Psychol.* **2011**, *2*, 154. https://doi.org/10.3389/fpsyg.2011.00154.

157 Klimesch, W.; Sauseng, P.; Hanslmayr, S. EEG alpha oscillations: The inhibition–timing hypothesis. *Brain Res. Rev.* **2007**, *53*, 63–88. https://doi.org/10.1016/j.brainresrev.2006.06.003.

158 Thut, G.; Nietzel, A.; Brandt, S.A.; Pascual-Leone, A. α-Band Electroencephalographic Activity over Occipital Cortex Indexes Visuospatial Attention Bias and Predicts Visual Target Detection. *J. Neurosci.* **2006**, *26*, 9494–9502. https://doi.org/10.1523/jneurosci.0875-06.2006.

159 Rihs, T.A.; Michel, C.M.; Thut, G. A bias for posterior α-band power suppression versus enhancement during shifting versus maintenance of spatial attention. *NeuroImage* **2009**, *44*, 190–199. https://doi.org/10.1016/j.neuroimage.2008.08.022.

160 Rihs, T.A.; Michel, C.M.; Thut, G. Mechanisms of selective inhibition in visual spatial attention are indexed by α-band EEG synchronization. *Eur. J. Neurosci.* **2007**, *25*, 603–610.

161 Sauseng, P.; Klimesch, W.; Stadler, W.; Schabus, M.; Doppelmayr, M.; Hanslmayr, S.; Gruber, W.R.; Birbaumer, N. A shift of visual spatial attention is selectively associated with human EEG alpha activity. *Eur. J. Neurosci.* **2005**, *22*, 2917–2926. https://doi.org/10.1111/j.1460-9568.2005.04482.x.

162 Foxe, J.J.; Simpson, G.V.; Ahlfors, S.P. Parieto-occipital ~1 0Hz activity reflects anticipatory state of visual attention mechanisms. *Neuroreport* **1998**, *9*, 3929–3933. https://doi.org/10.1097/00001756-199812010-00030.

163 Worden, M.S.; Foxe, J.J.; Wang, N.; Simpson, G.V. Anticipatory biasing of visuospatial attention indexed by retinotopically specific α-band electroencephalography increases over occipital cortex. *J. Neurosci.* **2000**, *20*, RC63–RC63.

164 Posner, M.I.; Snyder, C.R.; Davidson, B.J. Attention and the detection of signals. *J. Exp. Psychol. Gen.* **1980**, *109*, 160.

165 O'Sullivan, A.E.; Lim, C.Y.; Lalor, E. Look at me when I'm talking to you: Selective attention at a multisensory cocktail party can be decoded using stimulus reconstruction and alpha power modulations. *Eur. J. Neurosci.* **2019**, *50*, 3282–3295. https://doi.org/10.1111/ejn.14425.

166 Tune, S.; Wöstmann, M.; Obleser, J. Probing the limits of alpha power lateralisation as a neural marker of selective attention in middle-aged and older listeners. *Eur. J. Neurosci.* **2018**, *48*, 2537–2550. https://doi.org/10.1111/ejn.13862.

167 Zanto, T.P.; Gazzaley, A. *Attention and Ageing*; Oxford University Press: Oxford, UK, 2014.

168 Stern, Y.; Arenaza-Urquijo, E.M.; Bartrés-Faz, D.; Belleville, S.; Cantilon, M.; Chetelat, G. Reserve, Resilience and Protective Factors PIA Empirical Definitions and Conceptual Frameworks Workgroup. Whitepaper: Defining and investigating cognitive reserve, brain reserve, and brain maintenance. *Alzheimer's Dement* **2020**, *16*, 1305–1311.

169 Jensen, O.; Mazaheri, A. Shaping Functional Architecture by Oscillatory Alpha Activity: Gating by Inhibition. *Front. Hum. Neurosci.* **2010**, *4*, 186. https://doi.org/10.3389/fnhum.2010.00186.

170 Ruhnau, P.; Hauswald, A.; Weisz, N. Investigating ongoing brain oscillations and their influence on conscious perception–network states and the window to consciousness. *Front. Psychol.* **2014**, *5*, 1230.

171 Cecere, R.; Rees, G.; Romei, V. Individual Differences in Alpha Frequency Drive Crossmodal Illusory Perception. *Curr. Biol.* **2015**, *25*, 231–235. https://doi.org/10.1016/j.cub.2014.11.034.

172 Maurer, C.; Mergner, T.; Bolha, B.; Hlavacka, F. Vestibular, visual, and somatosensory contributions to human control of upright stance. *Neurosci. Lett.* **2000**, *281*, 99–102. https://doi.org/10.1016/s0304-3940(00)00814-4.

173 Jacobs, J.V.; Horak, F.B. Cortical control of postural responses. *J. Neural Transm.* **2007**, *114*, 1339–1348. https://doi.org/10.1007/s00702-007-0657-0.

174 Ozdemir, R.A.; Contreras-Vidal, J.L.; Paloski, W.H. Cortical control of upright stance in elderly. *Mech. Ageing Dev.* **2018**, *169*, 19–31. https://doi.org/10.1016/j.mad.2017.12.004.

175 Edwards, A.E.; Guven, O.; Furman, M.D.; Arshad, Q.; Bronstein, A.M. Electroencephalographic correlates of continuous postural tasks of increasing difficulty. *Neuroscience* **2018**, *395*, 35–48.

176 Hülsdünker, T.; Mierau, A.; Neeb, C.; Kleinöder, H.; Strüder, H. Cortical processes associated with continuous balance control as revealed by EEG spectral power. *Neurosci. Lett.* **2015**, *592*, 1–5. https://doi.org/10.1016/j.neulet.2015.02.049.

177 Sipp, A.R.; Gwin, J.T.; Makeig, S.; Ferris, D.P.; Malcolm, B.R.; Foxe, J.J.; Butler, J.S.; Molholm, S.; De Sanctis, P.; Peterson, S.M.; et al. Loss of balance during balance beam walking elicits a multifocal theta band electrocortical response. *J. Neurophysiol.* **2013**, *110*, 2050–2060. https://doi.org/10.1152/jn.00744.2012.

178 Ray, W.J.; Cole, H.W. EEG Alpha Activity Reflects Attentional Demands, and Beta Activity Reflects Emotional and Cognitive Processes. *Science* **1985**, *228*, 750–752. https://doi.org/10.1126/science.3992243.

179 Scurry, A.N.; Lovelady, Z.; Lemus, D.M.; Jiang, F. Impoverished inhibitory control exacerbates multisensory impairments in older fallers. *Front. Aging Neurosci.* **2021**, *13*, 700787.

3. Age-Related Changes in the Attentional Modulation of Temporal Binding

3.1. Linking Statement

Chapter 3 is the first data chapter of this thesis, which investigated how the interaction between bottom-up and top-down mechanisms in multisensory integration may change as a function of healthy ageing. As discussed throughout Chapter 2, the increased multisensory integration experienced by older adults may be attributed to age-related changes in the interplay between bottom-up, perceptual processing and top-down cognitive control. Specifically, this study measured whether attentional control could modulate the width of the temporal binding window to improve temporal precision during audiovisual integration, and how this interplay may differ between younger and older adults. Analysing behavioural data from 30 younger adults and 30 older adults in the stream-bounce task revealed that older adults may have attentional deficits associated with multisensory integration. Older adults found it more difficult to suppress task-irrelevant information than younger adults and therefore produced a less accurate multisensory performance.

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Age-related changes to the attentional modulation of temporal binding

Jessica L. Pepper[1] · Barrie Usherwood[1] · Theodoros M. Bampouras[2] · Helen E. Nuttall[1]

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3.2. Abstract

During multisensory integration, the time range within which visual and auditory information can be perceived as synchronous and bound together is known as the temporal binding window (TBW). With increasing age, the TBW becomes wider, such that older adults erroneously, and often dangerously, integrate sensory inputs that are asynchronous. Recent research suggests that attentional cues can narrow the width of the TBW in younger adults, sharpening temporal perception and increasing the accuracy of integration. However, due to their age-related declines in attentional control, it is not yet known whether older adults can deploy attentional resources to narrow the TBW in the same way as younger adults. This study investigated the age-related changes to the attentional modulation of the TBW. Thirty younger and 30 older adults completed a cued-spatial-attention version of the stream-bounce illusion, assessing the extent to which the visual and auditory stimuli were integrated when presented at three different stimulus-onset asynchronies, and when attending to a validly cued or invalidly cued location. A 2 × 2 × 3 mixed ANOVA revealed that when participants attended to the validly cued location (i.e., when attention was present), susceptibility to the stream-bounce illusion decreased. However, crucially, this attentional manipulation significantly affected audiovisual integration in younger adults, but not in older adults. These findings suggest that older adults have multisensory integration-related attentional deficits. Directions for future research and practical applications surrounding treatments to improve the safety of older adults' perception and navigation through the environment are discussed.

Keywords Ageing · Attention · Temporal binding · Multisensory integration

✉ Jessica L. Pepper
j.l.pepper@lancaster.ac.uk

Barrie Usherwood
b.usherwood@lancaster.ac.uk

Theodoros M. Bampouras
t.bampouras@ljmu.ac.uk

Helen E. Nuttall
h.nuttall1@lancaster.ac.uk

1 Department of Psychology, Fylde College, Lancaster University, Lancaster, UK LA1 4YF

2 School of Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, UK L3 3AF

3.3. Introduction

During multisensory processing, a key factor required to ascertain whether two sensory inputs are related is their temporal proximity (Hillock et al., 2011; Vroomen & Keetels, 2010). If auditory and visual inputs are presented closely together in time, they are more likely to be perceived as originating from the same event (Stevenson et al., 2012; Meredith & Stein, 1986) and bound together into a single, multisensory perceptual entity (Spence & Squire, 2003; Zampini et al., 2005). The adjustable time range within which visual and auditory stimuli can be perceived as synchronous and thus have an increased likelihood of being integrated is known as the temporal binding window (TBW; Bedard & Barnett-Cowan, 2016; Mégevand et al., 2013; Mozolic et al., 2012). The TBW allows two congruent sensory inputs to be integrated even if there is a degree of temporal discrepancy (e.g., due to differences in the speed of light versus sound, or differences in sensory propagation time; Mégevand et al., 2013; Pöppel et al., 1990; Stevenson et al., 2012). Likewise, bimodal sensory information that does not occur within the limits of the TBW will not be perceived concurrently, and therefore will not be bound together and can correctly remain discrete (Stevenson et al., 2012).

The width of the TBW is believed to widen with healthy ageing (Bedard & Barnett-Cowan, 2016; Diederich et al., 2008; Poliakoff et al., 2006; Setti et al., 2014). It has been well established in psychophysical research that older adults integrate more sensory information than younger adults, showing faster reaction times and greater accuracy in response to multisensory stimuli than unisensory stimuli (Laurienti et al., 2004, 2006; Peiffer et al., 2007). Recent research has postulated that this multisensory 'enhancement' exhibited by older adults may be due to a combination of their wider TBW and their attentional deficits. Specifically, age-related deficits in allocating the necessary attentional resources required for the top-down modulation of sensory processing could mean that, for older adults, the boundaries of the TBW are less restricted (Setti et al., 2011). As such, due to having a greater time range over which integration can occur, older adults then demonstrate increased integration across multiple modalities (Brooks et al., 2018) compared with the integration exhibited by younger adults (Laurienti et al., 2006; Peiffer et al., 2007). This increased integration is advantageous for older adults when the unisensory inputs are congruent and should contextually be bound together (Laurienti et al., 2006) yet can cause errors in perceptual performance if incongruent information is integrated when it should remain discrete (Poliakoff et al., 2006; Setti et al., 2014).

In everyday life, incorrectly identifying whether stimuli from different modalities should be integrated or segregated can lead to inaccurate and dangerous perceptions of the immediate environment (Bedard & Barnett-Cowan, 2016; Wise & Barnett-Cowan, 2018). This is evident in the fact that wider TBWs are associated with an increased risk of falls in older adults (Mahoney et al., 2014, 2019; Peterka, 2002; Setti et al., 2011)—when task-irrelevant sensory information is incorporated into the representation of the physical world, this could provoke distractibility and lead to a fall (Peiffer et al., 2007; Setti et al., 2011). From this safety perspective, it is clear how important it is to investigate if and how the TBW can be narrowed by attentional control, in order to sharpen perception and increase the ability of older adults to keep irrelevant information separate from meaningful sensory inputs in their dynamic environment.

Ostensibly, manipulating attentional cues could be a promising mechanism to narrow the TBW of older adults (Setti et al., 2011). However, the limited evidence surrounding how attentional abilities change with healthy ageing suggests that older adults find it more difficult than younger adults to focus their attention on only task-relevant information and inhibit the processing of task-irrelevant information (Gazzaley et al., 2005; Healey et al., 2008; Park & Reuter-Lorenz, 2009; Zhuravleva et al., 2014)—this has been termed the 'inhibitory deficit hypothesis' (Alain & Woods, 1999; Hasher & Zacks, 1988).

Donohue et al. (2015) implemented a cued-spatial-attention version of the stream-bounce illusion with younger adults to investigate how attentional mechanisms modulate the width of the TBW. In the stream-bounce illusion, the visual motion of the circles is always identical and task-relevant; however, when a task-irrelevant sound is played at the same time as the circles intersect, the auditory and visual sensory inputs are bound together (Fig. 1). This results in the perception that the circles "bounced off" rather than "passed through" each other. Donohue et al.'s findings indicated that attending to the validly cued location (i.e., viewing the full visual motion of the circles) could narrow the width of the TBW in younger adults, producing more accurate judgements regarding the temporal alignment of the visual and auditory information, and thus whether they should be integrated.

Despite this, it is not yet known whether older adults are able to deploy the necessary attentional resources required to narrow their TBW as effectively as younger adults can. The present study investigated whether there are age-related changes in this attentional modulation of the TBW, comparing the judgements and reaction times of younger and older adults in a cued-spatial-attention version of the stream-bounce task.

Firstly, it is predicted that due to their wider TBW, older adults will be more prone to binding together the visual input of the circles intersecting with the auditory input of the task-irrelevant tone, even if they do not occur synchronously. This will manifest as older adults providing a greater proportion of "bounce" responses in the stream-bounce illusion than younger adults at longer stimulus-onset

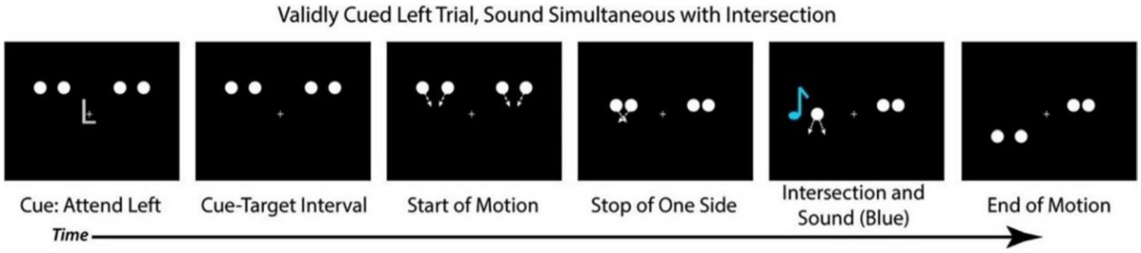


Fig. 1 Diagram of the cued-spatial-attention stream-bounce illusion. Image taken from the published manuscript of Donohue et al. (2015). (Colour figure online)

asynchronies (SOAs), confirming previous research (Bedard & Barnett-Cowan, 2016).

Secondly, it is predicted that across age groups, the proportion of "bounce" responses will be greater in the invalidly cued conditions than in the validly cued conditions. Participants are likely to display increased uncertainty if they are not attending to the full "X" shaped motion of the visual stimuli, the TBW will not be narrowed due to the absence of attention, and participants will perceive the visual and auditory information as synchronous at longer SOAs (Donohue et al., 2015).

Finally, it is predicted that due to the postulated attentional deficits of older adults, they will display less of a difference in the proportion of "bounce" responses in the validly cued versus invalidly cued conditions, compared with the difference produced by younger adults. In other words, the attentional manipulation may have less of an effect on multisensory integration in older adults than in younger adults. These a priori predictions were preregistered prior to data collection on www.aspredicted.org, project ID #65513 (https://aspredicted.org/zx9ev.pdf).

3.4. Method

3.4.1. Participants

This study used a total of 60 participants; 30 younger adults (15 males, 15 females) between 18 and 35 years old (*M* = 21.37, *SD* = 1.30) and 30 older adults (11 males, 19 females) between 60 and 80 years old (*M* = 67.91, *SD* = 4.71). This sample size was determined via an a priori power analysis using the ANOVA_exact Shiny app (Lakens & Caldwell, 2019; see preregistration on www.aspredicted.org, project ID #65513, https://aspredicted.org/zx9ev.pdf). Based on the large effect size (Cohen's f = 0.4) from similar studies (Basharat et al., 2019; Bedard & Barnett-Cowan, 2016; Chen et al., 2021; Donohue et al., 2015), an alpha value of p = .05 and power of 80%, the minimum sample size required was 30 participants per group.

All participants were fluent English speakers. Participants were required to have normal or corrected-to-normal vision, screened for via self-report. Participants were ineligible to proceed with the experiment if they had a history or current diagnosis of neurological conditions (e.g., epilepsy, mild cognitive impairment, dementia, Parkinson's disease) or learning impairments (e.g., dyslexia), or had hearing loss resulting in the wearing of hearing aids.

Participants were recruited via opportunity sampling; the majority of younger participants were students at Lancaster University and were known to the researcher, whilst the majority of older participants were members of the Centre for Ageing Research at Lancaster University. All participants provided informed consent.

3.4.2. Pre-screening tools

Participants were asked to complete two pre-screening questionnaires using Qualtrics survey software (www.qualtrics. com), to assess their eligibility for the study.

Speech, Spatial and Quality of Hearing Questionnaire (SSQ; Gatehouse & Noble, 2004; Appendix A)

Participants rated their hearing ability in different acoustic scenarios using a sliding scale from 0 to 10 (0 = *not at all*; 10 = *perfectly*). Whilst, at present, no defined cut-off score on the SSQ is available as a parameter to inform decision-making, previous studies have indicated that a mean score of 5.5 is indicative of moderate hearing loss (Gatehouse & Noble, 2004). As a result, people whose average score on the SSQ was lower than 5.5 were not eligible to participate in the experiment.

Informant Questionnaire on Cognitive Decline in the Elderly (IQ-CODE; Jorm, 2004; Appendix B)

Participants used a self-reported version of the IQ-CODE to rate how their performance in certain tasks now has changed compared with 10 years ago, answering on a 5-point Likert scale (1 = *much improved*; 5 = *much worse*). An average score of approximately 3.3 is the usual cut-off point when evaluating cognitive impairment and dementia (Jorm, 2004); therefore, people whose average score was higher than 3.3 were not eligible to participate in the experiment.

The mean scores produced by younger and older adults in each pre-screening questionnaire are displayed in Table 1, with individual scores displayed in Figs. 2 and 3. A Mann–Whitney U test revealed that there was no significant difference between age groups on the SSQ questionnaire [$U(N_{\text{Younger}} = 30, N_{\text{Older}} = 30) = 353.00, p = .15$]; however, there was a significant difference between age groups on the IQ-CODE questionnaire [$U(N_{\text{Younger}} = 30, N_{\text{Older}} = 30) = 4.00, p < .001$].

Table 1 Mean scores on the SSQ and IQ-CODE prescreening questionnaires, for both younger and older adults (standard deviations displayed in parentheses)

Age group	SSQ	IQ-CODE
Younger	8.34 *(1.10)*	1.74 *(0.51)*
Older	8.67 *(1.13)*	3.03 *(0.09)*

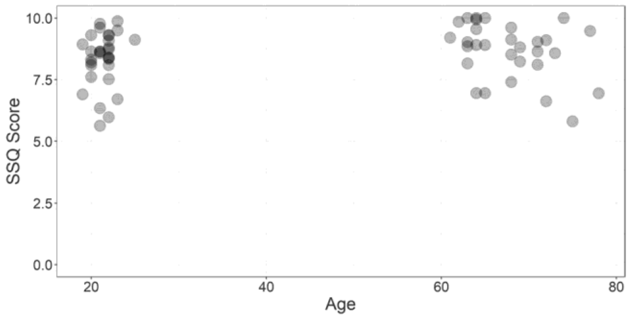


Fig. 2 SSQ scores of younger and older adults. Each point represents the score of each individual participant

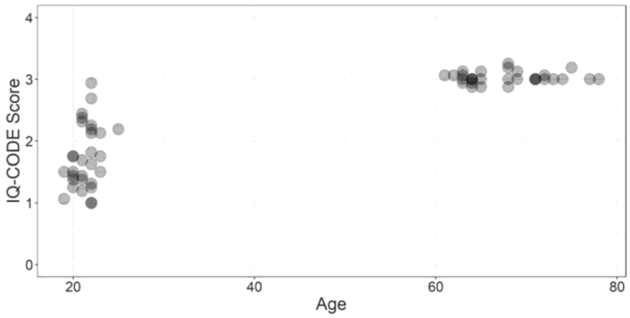


Fig. 3 IQ-CODE scores of younger and older adults. Each point represents the score of each individual participant

3.4.3. Experimental design

This research implemented a 2 (age: younger vs older) × 2 (cue: valid vs invalid) × 4 (stimulus onset asynchrony [SOA]: visual only [VO] vs 0 milliseconds vs 150 milliseconds vs 300 milliseconds) mixed design, with age as a between-subjects factor and cue and SOA as within-subjects factors.

The experiment consisted of 16 different trial conditions (Table 2), randomized across all participants. Replicating the paradigm used by Donohue et al. (2015), the experimental block contained 72 validly cued trials and 24 invalidly cued trials, which were equally distributed between each side of the screen (left/right) and SOA conditions; this means that each participant completed 144 valid trials and 48 invalid trials for each SOA.

Table 2 Number of trials within each cue and SOA condition.

SOA (ms)	Cue			
	Valid (Left) *N*	Valid (Right) *N*	Invalid (Left) *N*	Invalid (Right) *N*
0	72	72	24	24
150	72	72	24	24
300	72	72	24	24
VO	72	72	24	24

3.4.4. Stimuli and materials

Participants were asked to complete the experiment online, in a quiet room on a desktop or laptop computer with a standard keyboard. All participants were asked to wear headphones/earphones. A volume check was conducted at the beginning of the experiment; participants were presented with a constant tone and asked to adjust the volume of this tone to a clear and comfortable level.

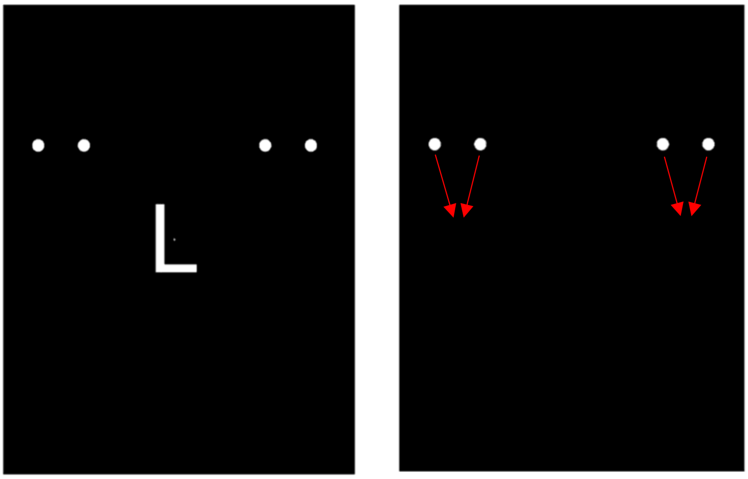
The stimuli used in the task were replicated from Donohue et al. (2015). Due to the fact that the experiment was completed remotely on participants' personal computers, we were unable to confirm whether the specifications of each monitor were identical. However, data recorded in Pavlovia confirmed that each participant experienced a refresh rate of 60 Hz. Each trial started with an attentional cue in the centre of the screen—a letter "L" or a letter "R" instructing participants to focus on the left or the right side of the screen. In addition to this, two pairs of circles were positioned at the top of the screen—one pair in the left hemifield and one pair in the right hemifield. Each circle was 1.5° in diameter and were presented 4° above the attentional cue; inner disks were 4.9° and outer disks were 10° left and right of the attentional cue. The attentional cue lasted for 1 second, and 650 milliseconds after this cue disappeared, the circles in each pair started to move towards each other downwards diagonally (i.e., the two left circles moving towards each other and the two right circles moving towards each other).

In the trials, one pair of circles moved towards each other, intersected, and continued on the same trajectory (fully overlapping and moving away from each other). This full motion of the circles formed an "X" shape, with the circles appearing to "stream" or "pass through" each other. On the opposite side of the screen, the other pair of circles stopped moving before they intersected, forming half of this "X" motion. On 75% of the trials, the full "X"-shaped motion appeared on the side of the screen that the cue directed participants towards (validly cued trials); on the other 25% of trials, the full motion occurred on opposite side of the screen to where the cue indicated, and the stopped motion occurred at the cued location (invalidly cued trials).

In addition to these visual stimuli, on 75% of the trials, an auditory stimulus was played binaurally (500 Hz, 17 milliseconds), either at the same time as the circles intersected (0-ms delay), 150 ms after the intersection or 300 ms after the intersection. The remaining 25% of the trials were visual-only (i.e., no sound was played). Participants were told that regardless of whether a sound was played, they must make their pass/bounce judgements based on the full motion of the circles (the “X” shape), even if the full motion occurred at the opposite side of the screen that they were attending to. Screen captures of a validly cued, 0ms SOA trial are displayed in Fig. 4. Participation lasted approximately 1 hour. The experiment was built in PsychoPy2 (Peirce et al., 2019) and hosted by Pavlovia (www.pavlovia.org).

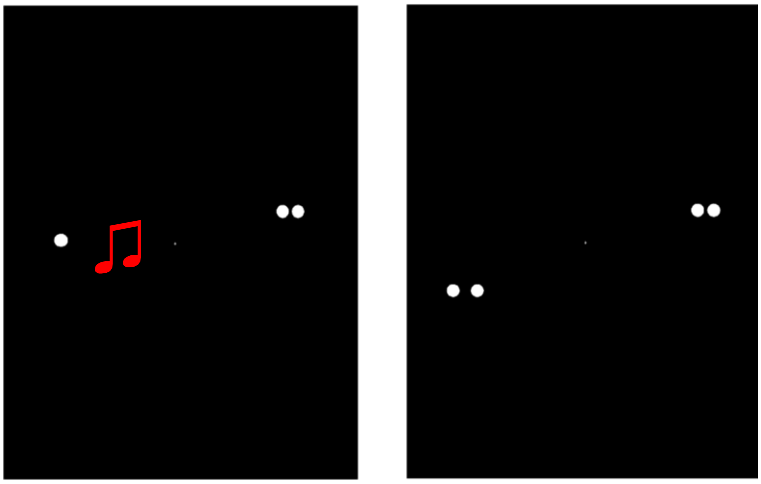
3.4.5. Procedure

Prior to the experiment, a brief online meeting was organized between the participant and the researcher to explain the task and answer any questions. Participants were emailed a link to a Qualtrics survey, which included the participant information sheet, consent form, demographic questions and pre-screening questionnaires. If the participant was deemed eligible to



1. Cue: Left

2. Both pairs of circles move towards each other



3. Circles on the right stop. Circles on the left intersect; tone plays

4. Circles on the left continue, moving away from each other; end of full “X” motion

Fig. 4 Screen captures of a validly cued trial (valid left), with an SOA of 0 ms (sound synchronous with intersection). Participants provided their pass/bounce judgement at the end of the trial. (Colour figure online) take part in the experiment, Qualtrics redirected participants to the experiment in Pavlovia.

Participants were then presented with instructions detailing the attentional cue elements of the task and asking them to base their judgements on the full X-shaped motion of the stimuli. Participants were asked to press “M” on the keyboard if they perceived the circles to “pass through” each other or press “Z” if they perceived the circles to “bounce off” each other, answering as quickly and as accurately as possible.

Participants completed a practice block of 10 trials, then the test session commenced. After each set of 10 random trials, participants had the opportunity to take a break. Participants were provided with a full debrief upon completion of the experiment, and all participants could enter a prize draw to win one of two £50 Amazon vouchers.

3.4.6. Statistical analyses

This study required four mixed ANOVAs—one for reaction times in visual-only unisensory conditions; one for reaction times in audiovisual multisensory (0 ms, 150 ms, 300 ms) conditions; one for bounce/pass judgements in visual-only unisensory conditions, and one for bounce/pass judgements in audiovisual multisensory (0 ms, 150 ms, 300 ms) conditions, following the analyses of Donohue et al. (2015).

Reaction times

For the first dependent variable of reaction time (RT), mean RTs were calculated for each participant in each Cue × SOA condition, representing the time taken, in milliseconds, for each participant to press “M” (“Pass Through”) or “Z” (“Bounce Off”) on the keyboard at the end of each trial. Responses (judgements or RTs) that were outside ±3 standard deviations were considered to be the result of different processes to the ones being examined (e.g., fast guesses or lack of attention; Whelan, 2008). Therefore, they were removed from subsequent analysis; this exclusion method was based on recommendations by Berger and Kiefer (2021). The RTs were then pooled and a grand mean was calculated and used for further analysis. As RTs are known to frequently deviate from normality (Whelan, 2008), the grand means were converted into *z*-scores, following the procedures recommended by Caldwell et al. (2019). A 2 (age: younger vs older) × 2 (cue: valid vs invalid) mixed ANOVA was then conducted on the *z*-score reaction times produced in the unisensory visual-only conditions, and a 2 (age: younger vs older) × 2 (cue: valid vs invalid) × 3 (SOA: 0 ms × 150 ms × 300 ms) mixed ANOVA was conducted on the *z*-score reaction times produced in the audiovisual multisensory conditions. As the unstandardized RT data showed a skewed distribution, medians and IQRs are also displayed graphically using boxplots, as suggested by Whelan (2008).

Bounce/pass judgements

For the second dependent variable of the bounce/pass judgements, the percentage of “bounce” responses provided in each Cue × SOA condition was calculated for each participant. Firstly, to address the violation of ANOVA assumptions present with percentage data, the proportion of “bounce” responses produced in the unisensory visual-only conditions was converted into *z*-scores. A 2 (age: younger vs older) × 2 (cue: valid vs invalid) mixed ANOVA was conducted on these standardized data from the unisensory condition. In addition, the proportion of “bounce” responses produced in the audiovisual conditions (SOAs of 0 ms, 150 ms, and 300 ms) were pooled and a grand mean was calculated and used for further analysis. These grand means were converted into z-scores, following the procedures recommended by Caldwell et al. (2019). A 2 (age: younger vs older) × 2 (cue: valid vs invalid) × 3 (SOA: 0 ms vs 150 ms vs 300 ms) mixed ANOVA was then conducted on these standardized *z*-score data from the multisensory conditions. Post hoc paired-samples *t* tests were also used to investigate significant differences between the 0 ms, 150 ms, 300 ms and visual-only SOA conditions. Mauchly’s test of sphericity was violated for the main effect of SOA, therefore Greenhouse–Geisser adjusted *p*-values were used where appropriate.

After the 2 × 2 × 3 mixed ANOVA on the audiovisual data, to analyze pairwise comparisons in the significant interaction of age and cue, responses in each SOA condition were collapsed—that is, a grand mean percentage of “bounce” responses was calculated by averaging the percentage of “bounce” responses in the 0 ms, 150 ms, and 300 ms trials in the valid condition and in the invalid condition. This produced an overall valid and an overall invalid mean percentage of “bounce” responses for each participant. As with the reaction time data and full bounce/pass data, these percentages were then pooled to allow calculation of the grand mean and subsequently converted to standardized *z*-scores, following the procedures recommended by Caldwell et al. (2019). Two separate one-way ANOVAs were conducted on this collapsed *z*-score data (“age” as the between-subjects factor, and valid or invalid as the within-subjects factor) to investigate differences between younger and older adults in the valid condition, and differences between younger and older adults in the invalid condition (Laerd, 2015). The datafile was then split by age, and a repeated-measures ANOVA using cue as the independent variable was conducted on this collapsed *z*-score data, to investigate differences between the proportion of “bounce” responses in the valid and invalid condition for younger adults, and in the valid and invalid condition for older adults (Laerd, 2015).

Data are presented as means and standard errors, and 95% confidence intervals are reported alongside the mean and the standard error for the bounce/pass analyses. Where two levels of a factor have been compared, the mean difference and standard error of this comparison has also been reported. An alpha level of .05 was used for all statistical tests. Statistical analyses were conducted using IBM SPSS Statistics for Windows (Version 25; IBM Corp., Armonk, NY, USA).

3.4.7. *Deviations from preregistration*

The analyses described in this manuscript differ from those outlined in the preregistration available on aspredicted.com. This is due to the implementation of recommendations from expert peer reviewers, which improved upon our original statistical analysis plan and validity of approach.

3.5. Results

3.5.1. *Analysis of reaction-time (RT) data: Assessing the effectiveness of the attentional manipulation*

RTs in response to all trials (i.e., both "pass through" and "bounce" responses) were included in the analyses, as unlike other two-alternative forced choice tasks, there was no specific "correct" response. The mean RTs in each condition, for each age group, are displayed in Figs. 5 and 6.

It was important to compare RTs for valid trials, where the full "X" motion occurred at the cued side of the screen, with RTs for invalid trials, where the full "X" motion occurred at the opposite, uncued side of the screen, to ensure that participants abided by the attentional manipulation; validly cued trials should produce faster RTs than invalidly cued trials (Donohue et al., 2015). As a result, cue was the variable of interest in these RT analyses.

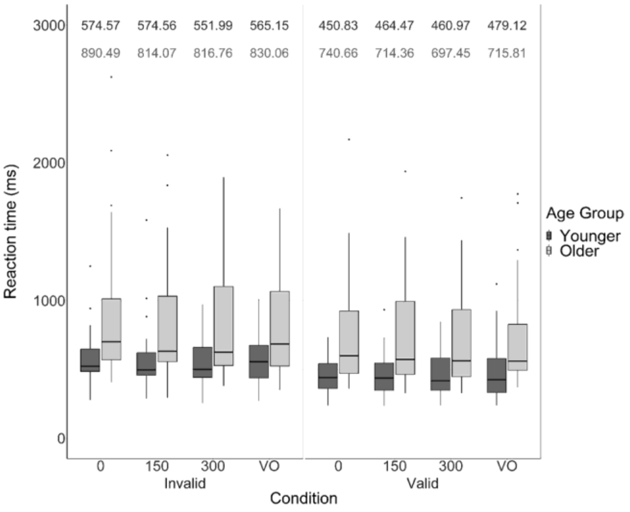


Fig. 5 Participant reaction times (RTs), in milliseconds, in each SOA and cue condition. Black bars represent the RTs of younger adults; grey bars represent the RTs of older adults. Each bar displays the median, the lower quartile and the upper quartile for each condition (outliers plotted separately). Numbers at the top of each panel indicate mean RTs—younger adult RTs are presented in the upper row in black, and older adult RTs are presented in the lower row in grey

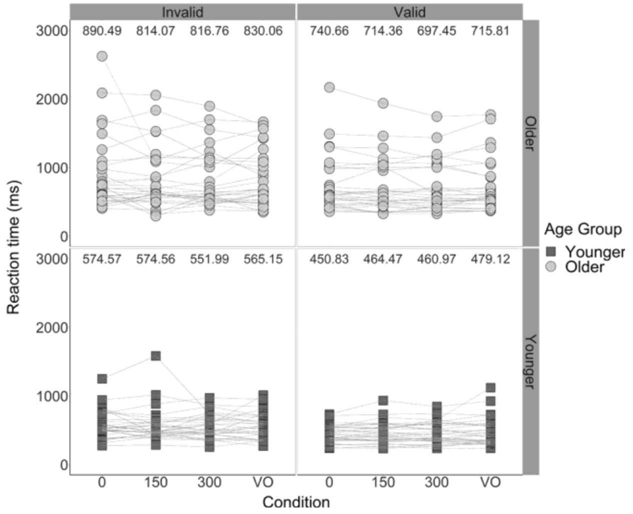


Fig. 6 Participant reaction times (RTs), in milliseconds, in each SOA and cue condition. Black squares represent the RTs of younger adults; grey circles represent the RTs of older adults. Participants' RTs across conditions are linked using lines. Numbers at the top of each panel display mean RTs in each condition

Reaction times: Unisensory conditions

A 2 (age: younger vs older) × 2 (cue: valid vs invalid) mixed ANOVA was conducted on the unisensory visual-only control conditions; there was a significant main effect of cue on the speed of key-press responses, $F(1, 58) = 17.24$, $p < .001$, $\eta_p^2 = 0.23$. Overall, participants were 100.14 ms faster at responding to validly cued trials compared with invalidly cued trials. In real-world contexts, simply attending to a specific location or modality speeds up reaction times, which is highly important for the safe and accurate perception of our environment (Mozolic et al., 2008). There was also a significant main effect of age on the speed of key-press responses, $F(1, 58) = 10.98$, $p = .002$, $\eta_p^2 = 0.16$—younger adults were 250.80 ms faster at responding than older adults. There was no significant interaction between age and cue, $F(1, 58) = 0.34$, $p = .561$, $\eta_p^2 = 0.006$.

Reaction times: Multisensory conditions

A 2 (age: younger vs older) × 2 (cue: valid vs invalid) × 3 (SOA: 0 ms vs 150 ms vs 300 ms) mixed ANOVA was then conducted on the RTs produced in the multisensory audiovisual conditions. These analyses indicated there was a significant main effect of cue on the speed of key-press responses, $F(1, 58) = 25.44$, $p < .001$, $\eta_p^2 = 0.31$—overall, participants were 115.53 ms faster at responding to the validly cued trials ($M = 588.21$ ms, $SE = 36.76$) compared with the invalidly cued trials ($M = 703.74$ ms, $SE = 43.20$), as displayed in Figs. 5 and 6. This suggests that the participants did attend to the validly cued side of the screen when directed, indicating that the attentional manipulation was effective. Using the same behavioural task, Donohue et al. (2015) found that their participants—a younger adult sample only—were 76 ms faster in the validly cued condition compared with the invalidly cued condition. As a result, the reaction time difference produced between cue conditions in the current experiment is meaningful and expected, yet larger than that produced in Donohue et al. (2015) due to the slower reaction times of older adults increasing the overall mean.

There was also a significant main effect of age on RTs, $F(1, 58) = 11.98$, $p = .001$, $\eta_p^2 = 0.17$—overall, younger adults ($M = 512.90$ ms, $SE = 54.35$) responded 226.07 ms faster than older adults ($M = 778.97$ ms, $SE = 54.35$), as displayed in Figs. 5 and 6. In a spatial attention task using younger and older adults, Madden (1990) found that younger adults were 184 ms faster than older adults, therefore it is fair to suggest that the reaction time difference generated by each age group in the current study is in line with previous literature. Whilst it was predicted that older adults would produce a slower response than younger adults, this result is indeed relevant to everyday life in that older adults could be slower at processing and responding to hazards in their dynamic environment. The resulting dangerous and inaccurate perception and action of older adults due to their slower reaction times may be associated with their increased risk of falls (Lajoie & Gallagher, 2004).

There was no significant main effect of SOA on RTs, $F(2, 116) = 2.11$, $p = .126$. There were no significant interactions between SOA and age, $F(2, 116) = 1.98$, $p = .143$, between SOA and cue, $F(2, 116) = 0.710$, $p = .494$, or between age and cue, $F(1, 58) = 0.102$, $p = .750$. Finally, the three-way interaction between cue, SOA and age was not significant, $F(2, 116) = 0.249$, $p = .780$.

3.5.2. *Analysis of bounce/pass judgements: Assessing the magnitude of multisensory integration*

The purpose of analyzing the proportion of "bounce" responses in each condition was to assess the magnitude of multisensory integration across the different SOAs and across attentional cues. "Bounce" was the response of interest as it was indicative of the participant integrating the visual (circles intersecting) and auditory (tone playing) information in the trial. The percentage of "bounce" responses produced in each Cue × SOA condition was calculated for each participant. The mean proportion of "bounce" responses within each condition, for each age group, are displayed in Fig. 7.

To illustrate the difference between the proportion of "bounce" responses in each of the audiovisual conditions compared with the visual-only control conditions, scatterplots were created with a horizontal reference line set at the mean proportion of "bounce" responses in the valid visual-only conditions (Fig. 8) and invalid visual-only conditions (Fig. 9), respectively.

Bounce/pass judgements: Unisensory conditions

It was first important to analyze the data from the 2 (age: younger vs older) × 2 (cue: valid vs invalid) mixed ANOVA that was conducted on the standardized "bounce" responses produced from the unisensory visual-only control conditions. In the visual-only ANOVA, there was no significant main effect of cue on the proportion of "bounce" responses, $F(1, 58) = 0.00$, $p = 1.000$, $\eta_p^2 = 0.00$, no significant main effect of age on the proportion of "bounce" responses, $F(1, 58) = 2.31$, $p = .134$, $\eta_p^2 = 0.038$, and no significant interaction between age and cue, $F(1, 58) = 2.02$, $p = .161$, $\eta_p^2 = 0.034$.

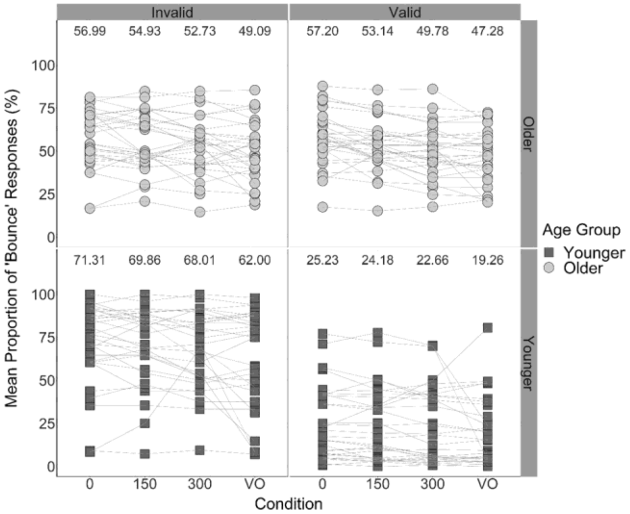


Fig. 7 Mean proportion of "bounce" responses in each Cue × SOA condition for each participant. Black squares represent data of younger adults; grey circles represent the data of older adults. Participants' "bounce" responses are linked across conditions using lines. Numbers at the top of each panel display the mean proportion of "bounce" responses in each condition

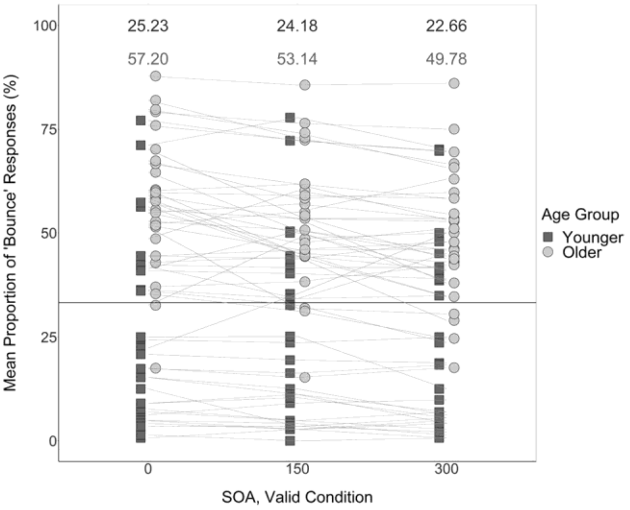


Fig. 8 Mean proportion of “bounce” responses produced by each participant in each of the validly cued audiovisual conditions. Solid black horizontal reference line at 33.27% represents the mean proportion of “bounce” responses produced in the validly cued visual-only conditions. Black squares represent the data of younger adults; grey circles represent the data of older adults. Participant “bounce” responses are linked across conditions using lines. Numbers at the top of the figure display mean proportions of “bounce” responses in each condition—the means of younger adults are presented in the upper row in black; the means of older adults are presented in the lower row in grey

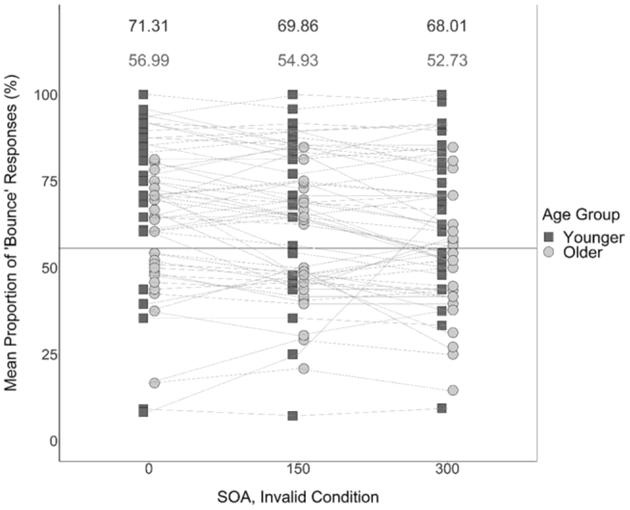


Fig. 9 Mean proportion of “bounce” responses produced by each participant in each of the invalidly cued audiovisual conditions. Solid black horizontal reference line at 55.55% represents the mean proportion of “bounce” responses produced in the invalidly cued visual-only conditions. Black squares represent the data of younger adults; grey circles represent the data of older adults. Participant “bounce” responses are linked across conditions using lines. Numbers at the top of the figure display mean proportions of “bounce” responses in each condition—the means of younger adults are presented in the upper row in black; the means of older adults are presented in the lower row in grey

Bounce/pass judgements: Multisensory conditions

For the participants’ bounce/pass judgements in the audiovisual conditions, a 2 (age: younger vs older) × 2 (cue: valid vs invalid) × 3 (SOA: 0 ms vs 150 ms vs 300 ms) mixed ANOVA was conducted.

To first assess whether there were differences in integration generally across age groups, the age variable in the 2 × 2 × 3 mixed ANOVA was examined. It was found that there was a significant main effect of age on the proportion of “bounce” responses, $F(1, 58) = 5.29$, $p = .025$, $\eta_p^2 = 0.084$. Overall, the proportion of “bounce” responses provided by older adults (M = 54.13%, SE = 2.23, 95% CI [49.66, 58.59]) was greater than the proportion of “bounce” responses provided by younger adults (M = 46.87%, SE = 2.23, 95% CI [42.41, 51.34]; mean difference = 7.26%, SE= 3.16), as displayed in Figs. 7 and 10. This suggests that older adults exhibited increased integration of the visual and auditory information compared with younger adults, which is an important finding as inefficient multisensory processing may be associated with increased risk of falls in older adults (Horak et al., 1989; Peiffer et al., 2007; Setti et al, 2011).

To investigate the effects of the attentional manipulation, it was important to assess the differences in validly cued vs invalidly cued conditions. The mixed ANOVA revealed a significant main effect of cue condition on the proportion of “bounce” responses, $F(1, 58) = 43.40$, $p < .001$, $\eta_p^2 = 0.43$.

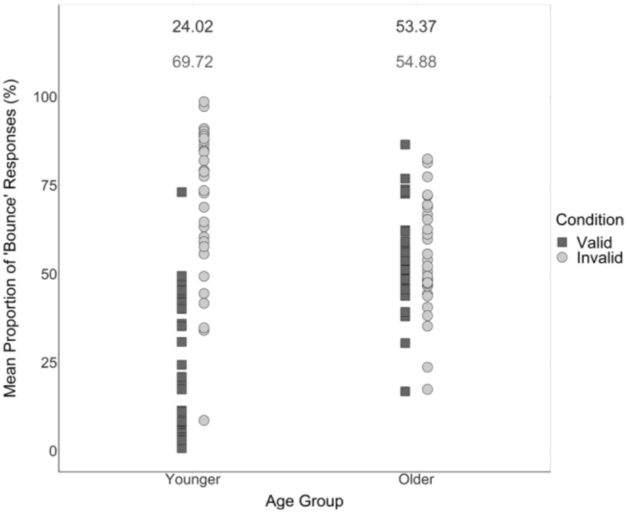


Fig. 10 Mean proportion of “bounce” responses produced by each younger and older adult in validly cued and invalidly cued conditions. Black squares represent “bounce” judgements in valid conditions; grey circles represent “bounce” judgements in invalid conditions. Numbers at the top of the figure display mean proportions of “bounce” responses in each condition—the means produced in the valid condition are presented in the upper row in black; the means produced in the invalid condition are presented in the lower row in grey

As displayed in Figs. 7 and 10, participants provided more "bounce" responses in the invalidly cued trials (*M* = 62.30%, *SE* = 2.45, 95% CI [57.39, 67.21]) compared with the validly cued trials (*M* = 38.70%, *SE* = 2.32, 95% CI [34.05, 43.34]; mean difference = 23.60%, *SE* = 3.58), in line with our hypothesis that the visual and auditory information is more likely to be perceived as synchronous and integrated in the invalidly cued condition (Donohue et al., 2015).

Mauchly's test of sphericity indicated that the assumption of sphericity was violated for the SOA factor, $\chi^2(2) = 36.72$, $p < .001$. Greenhouse–Geisser adjusted *p*-values indicated that there was a significant main effect of SOA on "bounce" responses, $F(1.36, 78.65) = 10.82$, $p < .001$, $\eta^2 = 0.16$. Posthoc paired-samples *t* tests revealed that 0-ms trials produced a significantly greater proportion of "bounce" responses than did 150-ms trials, $t(59) = 3.01$, $p = .004$; mean difference = 2.16%, *SE* = 0.71; 300-ms trials, $t(59) = 3.58$, $p = .001$; mean difference = 4.39%, *SE* = 1.22; and visual-only trials, $t(59) = 4.07$, $p < .001$; mean difference = 8.27%, *SE* = 2.05. In addition, 150-ms trials produced a significantly greater proportion of "bounce" responses than 300-ms trials, $t(59) = 2.77$, $p = .008$; mean difference = 2.23%, *SE* = 0.82, and visual-only trials, $t(59) = 3.35$, $p = .001$; mean difference = 6.12%, *SE* = 1.84. Finally, 300-ms trials produced a greater proportion of "bounce" responses than visual-only trials, $t(59) = 2.59$, $p = .012$; mean difference = 3.89%, *SE* = 1.51. This is in line with previous research (Watanabe & Shimojo, 2001) suggesting that the temporal proximity of the visual and auditory information in the stream-bounce illusion influences whether they are integrated, with shorter SOAs producing more "bounce" responses. The descriptive statistics of these SOA comparisons are displayed in Table 3.

The interaction between age and cue was significant, $F(1, 58) = 38.03$, $p < .001$, $\eta_p^2 = 0.40$. This contrasts with the pattern of results found for the visual-only ANOVA, in which this significant interaction was not present. Our findings indicate that age and attention influence the multisensory integration of the auditory and visual information in this task. In line with our hypothesis, there were age-related differences in how the attentional manipulation affected multisensory integration and thus the proportion of "bounce" responses. As a result, it was necessary to analyze the pairwise comparisons of this interaction to investigate where these differences exist.

Table 3 Means and standard errors of the proportion of "bounce" responses provided at each level of the SOA condition (0 ms, 150 ms, 300 ms, visual-only)

	SOA			Visual-only
	0	150	300	
M, %	52.68	50.52	48.29	44.41
SE	1.85	1.65	1.66	1.85
95% CI	[49.14, 56.22]	[47.32, 53.73]	[45.03, 51.56]	[40.81, 48.00]

Bounce/pass judgements: Pairwise comparisons

To analyze pairwise comparisons within the age and cue interaction, the "bounce" responses in each audiovisual SOA condition were collapsed, so that a mean percentage of "bounce" responses provided by each participant could be calculated for validly cued and invalidly cued conditions. These percentages were then converted to standardized *z*-scores (see Statistical Analyses section).

Age pairwise comparisons To assess differences between the proportion of "bounce" responses provided by younger adults and older adults in valid trials, and the differences between younger and older adults in invalid trials, two separate one-way ANOVAs were conducted (see Statistical Analyses section).

The first one-way ANOVA analyzed responses in the valid condition, and revealed that there were significant differences in the proportion of "bounce" responses between age groups, $F(1, 58) = 40.03$, $p < .001$. In the valid condition, a significantly greater proportion of "bounce" responses were produced by older adults (*M* = 53.37%, *SE* = 2.61, 95% CI [48.04, 58.70]) than younger adults (*M* = 24.02%, *SE* = 3.84, 95% CI [16.17, 31.87]).

In addition, the second one-way ANOVA analyzed responses in the invalid condition, and also indicated a significant difference between age groups, $F(1, 58) = 9.15$, $p = .004$. In the invalid condition, a significantly greater proportion of "bounce" responses were produced by younger adults (*M* = 69.72%%, *SE* = 3.97, 95% CI [61.61, 77.84]) than by older adults (*M* = 54.88%, *SE* = 2.89, 95% CI [48.97, 60.79]). These differences are displayed graphically in Fig. 10.

Cue pairwise comparisons To assess differences in the proportion of "bounce" responses provided by younger adults in valid versus invalid trials, and by older adults in valid versus invalid trials, a repeated-measures ANOVA was conducted on the collapsed *z*-score data.

When examining the data of younger adults, the ANOVA revealed that there was a significant difference in the proportion of "bounce" responses in validly cued and invalidly cued trials, $F(1, 29) = 47.76$, $p < .001$, $\eta_p^2 = 0.62$. Overall, younger adults produced a significantly greater proportion of "bounce" responses in invalidly cued trials (*M* = 69.72%, *SE* = 3.97, 95% CI [61.61, 77.84]) compared with validly cued trials (*M* = 24.02%, *SE* = 3.84, 95% CI [16.17, 31.87]; mean difference = 45.71%, *SE* = 6.61).However, when examining the data of older adults, it was revealed that there was no significant difference in the proportion of "bounce" responses in the validly cued and invalidly cued trials, $F(1, 29) = 0.30$, $p = .589$, $\eta_p^2 = 0.01$. Overall, older adults produced a similar proportion of "bounce" responses in the valid trials (*M* = 53.37%, *SE* = 2.61, 95% CI [48.04, 58.71]) as in the invalid trials (*M* = 54.88%, *SE* = 2.89, 95% CI [48.98, 60.79]; mean difference = 1.51%, *SE* = 2.76). Taken together, this suggests that, in line with our hypothesis, the multisensory integration of older adults was less affected by the attentional manipulation than younger adults. These differences are displayed in Fig. 10.

There was no significant interaction between cue and SOA, $F(2, 116) = 0.42$, $p = .658$, $\eta_p^2 = 0.01$, or between age and SOA, $F(2, 116) = 1.21$, $p = .303$, $\eta_p^2 = 0.02$. In addition, the three-way interaction between age, cue, and SOA was not significant, $F(2, 116) = 1.06$, $p = .349$, $\eta_p^2 = 0.018$. This means that conclusions cannot be made regarding how the width of the TBW, or the attentional modulation of the TBW, changes with healthy ageing.

3.6. Discussion

The aim of this study was to investigate how the attentional modulation of the TBW changes as a function of ageing, replicating the paradigm of Donohue et al. (2015) to assess whether attentional cues can narrow the TBW in older adults in the same way that they were found to in younger adults. Upon analysis of the proportion of "bounce" responses produced in the unisensory visual-only conditions, as expected, there were no significant main effects of age or cue, and no significant interaction between age and cue. However, after analyzing the proportion of "bounce" responses produced in the multisensory audiovisual conditions, there were significant main effects of age and cue, and a significant interaction between age and cue. Arguably the most important finding of this study was that the attentional manipulation interacted with age in the multisensory conditions: spatial attention did not significantly influence the audiovisual integration of older adults, yet it did influence the integration of younger adults. This strongly suggests that older adults may have attentional deficits compared with younger adults, specifically associated with multisensory integration.

The crucial significant interaction between age and cue in the multisensory conditions was in line with our original hypothesis; younger adults produced a significant difference in the proportion of "bounce" responses between validly cued and invalidly cued conditions, and older adults produced a nonsignificant difference. If this finding indicates that older adults do have attentional deficits relative to younger adults (Gazzaley, 2013; Healey et al., 2008; Poliakoff et al., 2006), it suggests that older adults displayed increased difficulty in inhibiting task-irrelevant information when it co-occurs with task-relevant information, even when presented at the attended location (Fabiani, 2012).

It is important to note that much of the literature that argues the contrary—that attentional mechanisms remain unchanged between younger and older adulthood—is based upon selective and spatial attention experiments implementing very simple stimuli and tasks, such as identifying the colour of a circle, or identifying whether a visual flash or an auditory beep was presented first (de Dieuleveult et al., 2017; Hugenschmidt et al., 2009; Peiffer et al., 2007). The cued-spatial-attention version of the stream-bounce illusion utilized in the current study is comparatively much more difficult than this due to the higher cognitive demands and decisional elements of the task (Bedard & Barnett-Cowan, 2016); not only do participants need to process the attentional cue and the fast-moving visual stimuli, but if they integrate the auditory stimuli, participants must then also use their knowledge regarding how objects make a sound when they collide to inform their decision-making (Watanabe & Shimojo, 2001). It is therefore likely that the complex stimuli and complex task implemented in this experiment allowed for the detection of age-related deficits in attentional control, whereas previous research that found attentional mechanisms to be preserved in older adults may have observed somewhat of a 'ceiling effect', being unable to identify declines in attentional control due to the ease and simplicity of the tasks employed (Houx et al., 2002). Whilst it is a strength of the current study that the measures implemented were sensitive enough to uncover these important age-related attentional deficits in multisensory integration, this highlights how research investigating the mechanisms involved in multisensory integration, and how these change with age, appears to be highly task-dependent and stimuli-specific (Barutchu et al., 2019).

The significant main effect of cue in the multisensory conditions indicated that as hypothesized, a greater proportion of "bounce" responses was produced in invalidly cued conditions than in validly cued conditions. Previous literature surrounding attentional cueing (Posner, 1980; Posner & Driver, 1992) would suggest that one reason for this, specifically when analyzing the performance of younger adults, is that attending to the validly cued side inhibited the processing of task-irrelevant auditory information, reducing the likelihood of it being integrated with task-relevant visual information (Donohue et al., 2015; Mozolic et al., 2008; Talsma et al., 2007, 2010). This would explain the lower proportion of "bounce" responses provided by younger adults in the validly cued trials versus invalidly cued trials; their strong attentional control allowed them to focus on the "streaming" motion of the visual stimuli and decrease the influence of the distracting auditory information on the percept (Donohue et al., 2015; Kawabe & Miura, 2006).

A second, related reason for the significant main effect of cue could be that when the full "X" motion occurred on the unattended side of the screen, participants are likely to have missed the start of the movement and the crucial intersection (Donohue et al., 2015). This creates uncertainty about the visual stimuli, therefore perhaps participants relied more heavily upon the auditory information in the trial to make their pass/bounce judgements in these instances. This uncertainty, coupled with the knowledge that a sound usually occurs when two objects collide in everyday life (Watanabe & Shimojo, 2001), may have induced more "bounce" representations at the invalidly cued location, as attention was not present to enhance the full veridical movement of the visual stimuli (Donohue et al., 2015).

There was also a significant main effect of age, with older adults providing a significantly greater proportion of "bounce" responses overall compared with younger adults. This indicates that, in partial correspondence with our hypothesis, older adults integrated the visual and auditory information more than younger adults did. Previous research would suggest that this increased integration is due to the wider TBW of older adults providing a greater time span over which integration can occur (Brooks et al., 2018; Mozolic et al., 2012; Setti et al., 2011). However, we did not find a significant interaction between age and SOA, nor a significant interaction between age, SOA, and cue. Whilst a limitation of the current study is that the exact screen specifications of each participant could not be controlled because participants completed the experiment remotely, this is unlikely to be the sole explanation as to why a significant interaction was not found here.

One potential explanation as to why the SOA factor was not involved in any significant interactions could be due to the auditory element of the task eliciting demand characteristics (Nichols & Maner, 2008). That is, the mere presence of the sound in a trial could have induced a "bounce" response if participants believed that the experiment was simply measuring whether they detected the sound and related it to the perception of bouncing (McCambridge et al., 2012). If "bounce" responses were produced at either location simply due to the presence of the sound rather than the relative timing of the sound, attention was not specifically serving to "narrow" the TBW.

Importantly, studies that have successfully manipulated SOAs to find that older adults have a wider TBW (Laurienti et al., 2006; Mahoney et al., 2011; Peiffer et al., 2007; Setti et al., 2011) have used static stimuli such as flashes and beeps, whereas studies which have used dynamic visual stimuli (Roudaia et al., 2013; Stephen et al., 2010), like that in the stream-bounce illusion, did not detect such age-related changes in the width of the TBW. As such, the efficacy of systematically manipulating SOAs to index the width of the TBW may vary depending on whether the multisensory illusion uses static or dynamic stimuli (Roudaia et al., 2013). Previous research has postulated that dynamic stimuli may require increased processing within the visual modality before it is integrated with stimuli from other modalities (Stevenson & Wallace, 2013), which would result in a wider TBW. Perhaps longer SOAs are needed when implementing dynamic stimuli compared with static stimuli, to accurately index this wider TBW and detect differences between age groups.

In sum, the results of this study provide interesting directions for future research. Firstly, given that dynamic stimuli are more likely to index visual motion perception than static stimuli (Roudaia et al., 2013), future studies should focus on using moving visual stimuli like the stream-bounce illusion does, as this would result in more ecologically valid conclusions regarding how multisensory integration occurs in dynamic, everyday life environments. However, as suggested, perhaps longer SOAs should be used if dynamic stimuli are implemented, accounting for the increased time taken to process the stimuli within the modality before it is integrated with stimuli from other modalities (Stevenson & Wallace, 2013). This could increase the likelihood of detecting age-related changes in the width of the TBW.

Future, in-person research using neuroscientific techniques such as fMRI or TMS would allow for the investigation of the neurobiological origins of the bottom-up and top-down mechanisms involved in multisensory integration, and how they are affected by healthy ageing. Uncovering age-related changes in the magnitude and/or sequence of activation in different brain areas during multisensory processing is essential for understanding the relative contributions of mechanisms like the TBW and attentional control in the creation of an accurate and reliable percept of our environment. This knowledge is increasingly relevant as it could support the development of targeted programmes or therapies to strengthen the attentional control of older adults, sharpening their perception and reducing the risk of falls in our ageing population.

3.7. Conclusion

To conclude, older adults in this experiment integrated more distracting, task-irrelevant information than younger adults. Crucially, however, the attentional manipulation within the task influenced audiovisual integration in older adults less than it influenced integration in younger adults, suggesting that older adults may have attentional deficits associated with multisensory integration. Manipulation of SOAs and assessing subsequent integration remains likely to be an effective way to index the width of the TBW; however, the stimulus specificity of the paradigms used must be considered. Future experiments employing dynamic stimuli could uncover more about how age-related changes in attentional control impact the temporal processing of multisensory stimuli, producing conclusions that are high in ecological validity. The findings of this would have significant practical applications in the development of clinical treatments to strengthen the attentional control of older adults, to enhance the temporal processing of task-relevant stimuli and inhibit the processing of distracting stimuli that should not be incorporated into the percept. Improving the multisensory perception of older adults in this way could greatly improve their ability to safely navigate through their environment and reduce their risk of falls.

Open practices statement The dataset used in this experiment is available online (https://doi.org/10.17635/lancaster/researchdata/568). The experiment described in this manuscript was preregistered at www.aspredicted.org, project ID #65513, https://aspredicted.org/zx9ev.pdf. The analyses described in this manuscript differ from those outlined in the preregistration available on aspredicted.com. This is due to the implementation of recommendations from expert peer-reviewers, which improved upon our original statistical analysis plan and validity of approach.

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Availability of data and materials The datasets generated during and/or analyzed during the current study are available in the Lancaster University Pure repository (https://doi.org/10.17635/lancaster/researchdata/568).

Code availability The SPSS syntax used in the current study is available in the Lancaster University Pure repository (https://doi.org/10. 17635/lancaster/researchdata/606).

Declarations

Ethics approval Ethics approval was obtained from the Department of Psychology Ethics Committee at Lancaster University. This study was performed in line with the principles of the Declaration of Helsinki.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The authors affirm that human research participants provided informed consent for publication of their data.

Conflicts of interest/competing interests The authors have no relevant financial or nonfinancial interests to disclose. The authors have no competing interests to declare that are relevant to the content of this article.

References

Alain, C., & Woods, D. L. (1999). Age-related changes in processing auditory stimuli during visual attention: Evidence for deficits in inhibitory control and sensory memory. *Psychology and Aging, 14*(3), 507.

Barutchu, A., Toohey, S., Shivdasani, M. N., Fifer, J. M., Crewther, S. G., Grayden, D. B., & Paolini, A. G. (2019). Multisensory perception and attention in school-age children. *Journal of Experimental Child Psychology, 180*, 141–155.

Basharat, A., Mahoney, J. R., & Barnett-Cowan, M. (2019). Temporal metrics of multisensory processing change in the elderly. *Multisensory Research, 32*(8), 715–744.

Bedard, G., & Barnett-Cowan, M. (2016). Impaired timing of audiovisual events in the elderly. *Experimental Brain Research, 234*(1), 331–340.

Berger, A., & Kiefer, M. (2021). Comparison of different response time outlier exclusion methods: A simulation study. *Frontiers in Psychology*, 2194.

Brooks, C. J., Chan, Y. M., Anderson, A. J., & McKendrick, A. M. (2018). Audiovisual temporal perception in aging: The role of multisensory integration and age-related sensory loss. *Frontiers in Human Neuroscience, 12*, 192.

Caldwell, J. A., Niro, P. J., Farina, E. K., McClung, J. P., Caron, G. R., & Lieberman, H. R. (2019). A *Z*-score based method for comparing the relative sensitivity of behavioral and physiological metrics including cognitive performance, mood, and hormone levels. *PLOS ONE, 14*(8), e0220749.

Chen, Y. C., Yeh, S. L., & Tang, P. F. (2021). Age-related changes in audiovisual simultaneity perception and their relationship with working memory. *The Journals of Gerontology: Series B, 76*(6), 1095–1103.

de Dieuleveult, A. L., Siemonsma, P. C., van Erp, J. B., & Brouwer, A. M. (2017). Effects of aging in multisensory integration: A systematic review. *Frontiers in Aging Neuroscience, 9*, 80.

Diederich, A., Colonius, H., & Schomburg, A. (2008). Assessing age-related multisensory enhancement with the time-window-of-integration model. *Neuropsychologia, 46*(10), 2556–2562.

Donohue, S. E., Green, J. J., & Woldorff, M. G. (2015). The effects of attention on the temporal integration of multisensory stimuli. *Frontiers in Integrative Neuroscience, 9*, 32.

Fabiani, M. (2012). It was the best of times, it was the worst of times: A psychophysiologist's view of cognitive aging. *Psychophysiology, 49*(3), 283–304.

Gatehouse, S., & Noble, W. (2004). The speech, spatial and qualities of hearing scale (SSQ). *International Journal of Audiology, 43*(2), 85–99.

Gazzaley, A. (2013). Top-down modulation deficit in the aging brain: An emerging theory of cognitive aging. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 593–608). Oxford University Press.

Gazzaley, A., Cooney, J. W., Rissman, J., & D'esposito, M. (2005). Top-down suppression deficit underlies working memory impairment in normal aging. *Nature Neuroscience, 8*(10), 1298–1300.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. *Psychology of Learning and Motivation, 22*, 193–225.

Healey, M. K., Campbell, K. L., & Hasher, L. (2008). Cognitive aging and increased distractibility: Costs and potential benefits. *Progress in Brain Research, 169*, 353–363.

Hillock, A. R., Powers, A. R., & Wallace, M. T. (2011). Binding of sights and sounds: Age-related changes in multisensory temporal processing. *Neuropsychologia, 49*(3), 461–467.

Horak, F. B., Shupert, C. L., & Mirka, A. (1989). Components of postural dyscontrol in the elderly: A review. *Neurobiology of Aging, 10*(6), 727–738.

Houx, P. J., Shepherd, J., Blauw, G. J., Murphy, M. B., Ford, I., Bollen, E. L., … Westendorp, R. G. (2002). Testing cognitive function in elderly populations: The PROSPER study. *Journal of Neurology, Neurosurgery & Psychiatry, 73*(4), 385–389.

Hugenschmidt, C. E., Mozolic, J. L., & Laurienti, P. J. (2009). Suppression of multisensory integration by modality-specific attention in aging. *NeuroReport, 20*(4), 349.

Jorm, A. F. (2004). The Informant Questionnaire on cognitive decline in the elderly (IQCODE): A review. *International Psychogeriatrics, 16*(3), 275.

Kawabe, T., & Miura, K. (2006). Effects of the orientation of moving objects on the perception of streaming/bouncing motion displays. *Perception & Psychophysics, 68*(5), 750–758.

Laerd, J. (2015). *Statistics: Understanding sphericity—An introduction to, testing for and interpreting sphericity.* Laerd Statistics. Retrieved September 1 2021 from https://statistics.laerd.com/stati stical-guides/sphericity-statistical-guide.php

Lajoie, Y., & Gallagher, S. P. (2004). Predicting falls within the elderly community: Comparison of postural sway, reaction time, the Berg balance scale and the Activities-specific Balance Confidence (ABC) scale for comparing fallers and non-fallers. *Archives of Gerontology and Geriatrics, 38*(1), 11–26.

Lakens, D., & Caldwell, A. R. (2019). Simulation-based power-analysis for factorial ANOVA designs. *PsyArXiv Preprints.* https://doi.org/ 10.31234/osf.io/baxsf

Laurienti, P. J., Kraft, R. A., Maldjian, J. A., Burdette, J. H., & Wallace, M. T. (2004). Semantic congruence is a critical factor in multisensory behavioural performance. *Experimental Brain Research, 158*(4), 405–414.

Laurienti, P. J., Burdette, J. H., Maldjian, J. A., & Wallace, M. T. (2006). Enhanced multisensory integration in older adults. *Neurobiology of Aging, 27*(8), 1155–1163.

Madden, D. J. (1990). Adult age differences in the time course of visual attention. *Journal of Gerontology, 45*(1), P9–P16.

Mahoney, J. R., Li, P. C. C., Oh-Park, M., Verghese, J., & Holtzer, R. (2011). Multisensory integration across the senses in young and old adults. *Brain Research, 1426*, 43–53.

Mahoney, J. R., Holtzer, R., & Verghese, J. (2014). Visual-somatosensory integration and balance: Evidence for psychophysical integrative differences in aging. *Multisensory Research, 27*(1), 17–42.

Mahoney, J. R., Cotton, K., & Verghese, J. (2019). Multisensory integration predicts balance and falls in older adults. *The Journals of Gerontology: Series A, 74*(9), 1429–1435.

McCambridge, J., De Bruin, M., & Witton, J. (2012). The effects of demand characteristics on research participant behaviours in non-laboratory settings: A systematic review. *PLOS ONE, 7*(6), e39116.

Mégevand, P., Molholm, S., Nayak, A., & Foxe, J. J. (2013). Recalibration of the multisensory temporal window of integration results from changing task demands. *PLOS ONE, 8*(8), e71608.

Meredith, M. A., & Stein, B. E. (1986). Spatial factors determine the activity of multisensory neurons in cat superior colliculus. *Brain Research, 365*(2), 350–354.

Mozolic, J. L., Hugenschmidt, C. E., Peiffer, A. M., & Laurienti, P. J. (2008). Modality-specific selective attention attenuates multisensory integration. *Experimental Brain Research, 184*(1), 39–52.

Mozolic, J. L., Hugenschmidt, C. E., Peiffer, A. M., & Laurienti, P. J. (2012). Multisensory integration and aging. In M. M. Murray & M. T. Wallace (Eds.), *The neural bases of multisensory processes* (Ch. 20). CRC Press.

Nichols, A. L., & Maner, J. K. (2008). The good-subject effect: Investigating participant demand characteristics. *The Journal of General Psychology, 135*(2), 151–166.

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: Aging and neurocognitive scaffolding. *Annual Review of Psychology, 60*, 173–196.

Peiffer, A. M., Mozolic, J. L., Hugenschmidt, C. E., & Laurienti, P.J. (2007). Age-related multisensory enhancement in a simple audiovisual detection task. *NeuroReport, 18*(10), 1077–1081.

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., … Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods, 51*(1), 195–203.

Peterka, R. J. (2002). Sensorimotor integration in human postural control. *Journal of Neurophysiology, 88*(3), 1097–1118.

Poliakoff, E., Ashworth, S., Lowe, C., & Spence, C. (2006). Vision and touch in ageing: Crossmodal selective attention and visuotactile spatial interactions. *Neuropsychologia, 44*(4), 507–517.

Pöppel, E., Schill, K., & von Steinbüchel, N. (1990). Sensory integration within temporally neutral systems states: A hypothesis. *Naturwissenschaften, 77*(2), 89–91.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*(1), 3–25.

Posner, M. I., & Driver, J. (1992). The neurobiology of selective attention. *Current Opinion in Neurobiology, 2*(2), 165–169.

Roudaia, E., Sekuler, A. B., Bennett, P. J., & Sekuler, R. W. (2013). Aging and audio-visual and multi-cue integration in motion. *Frontiers in Psychology, 4*, 267.

Setti, A., Burke, K. E., Kenny, R. A., & Newell, F. N. (2011). Is inefficient multisensory processing associated with falls in older people? *Experimental Brain Research, 209*(3), 375–384.

Setti, A., Stapleton, J., Leahy, D., Walsh, C., Kenny, R. A., & Newell, F. N. (2014). Improving the efficiency of multisensory integration in older adults: Audio-visual temporal discrimination training reduces susceptibility to the sound-induced flash illusion. *Neuropsychologia, 61*, 259–268.

Spence, C., & Squire, S. (2003). Multisensory integration: Maintaining the perception of synchrony. *Current Biology, 13*(13), R519–R521.

Stephen, J. M., Knoefel, J. E., Adair, J., Hart, B., & Aine, C. J. (2010). Aging-related changes in auditory and visual integration measured with MEG. *Neuroscience Letters, 484*(1), 76–80.

Stevenson, R. A., & Wallace, M. T. (2013). Multisensory temporal integration: Task and stimulus dependencies. *Experimental Brain Research, 227*(2), 249–261.

Stevenson, R. A., Fister, J. K., Barnett, Z. P., Nidiffer, A. R., & Wallace, M. T. (2012). Interactions between the spatial and temporal stimulus factors that influence multisensory integration in human performance. *Experimental Brain Research, 219*(1), 121–137.

Talsma, D., Doty, T. J., & Woldorff, M. G. (2007). Selective attention and audiovisual integration: Is attending to both modalities a prerequisite for early integration? *Cerebral Cortex, 17*(3), 679–690.

Talsma, D., Senkowski, D., Soto-Faraco, S., & Woldorff, M. G. (2010). The multifaceted interplay between attention and multisensory integration. *Trends in Cognitive Sciences, 14*(9), 400–410.

Vroomen, J., & Keetels, M. (2010). Perception of intersensory synchrony: A tutorial review. *Attention, Perception, & Psychophysics, 72*(4), 871–884.

Watanabe, K., & Shimojo, S. (2001). When sound affects vision: Effects of auditory grouping on visual motion perception. *Psychological Science, 12*(2), 109–116.

Whelan, R. (2008). Effective analysis of reaction time data. *The Psychological Record, 58*, 475–482.

Wise, A., & Barnett-Cowan, M. (2018). Perceived simultaneity and temporal order of audiovisual events following concussion. *Frontiers in Human Neuroscience, 12*, 139.

Zampini, M., Guest, S., Shore, D. I., & Spence, C. (2005). Audio-visual simultaneity judgments. *Perception & Psychophysics, 67*(3), 531–544.

Zhuravleva, T. Y., Alperin, B. R., Haring, A. E., Rentz, D. M., Holcomb, P. J., & Daffner, K. R. (2014). Age-related decline in bottom-up processing and selective attention in the very old. *Journal of Clinical Neurophysiology: Official Publication of the American Electroencephalographic Society, 31*(3), 261.

4. Age-Related Changes in Functional Balance Ability Predict Alpha Activity During Multisensory Integration

4.1. Linking Statement

Chapter 4 builds upon the findings of Chapter 3, with the aim of investigating the neural correlates of older adults' weaker attentional modulation during multisensory integration. If older adults find it more difficult to ignore distracting, task-irrelevant information, this may be reflected in differences in alpha synchronisation between younger and older adults (Wostmann et al., 2015). Crucially, age-related differences in alpha power may associate with an older adults' weaker functional ability and increased fall risk, given the important role of attentional control in balance maintenance (Kahya et al., 2019; Zhang et al., 2020). Participants completed the stream-bounce task whilst their parieto-occipital alpha activity was recorded using EEG, to analyse whether alpha power predicts multisensory performance in the task. Participants' balance abilities were also measured, using functional ability and sway velocity as a proxy for fall risk in each age group. Taken together, this study explored whether age-related changes in audiovisual integration could be predicted by alpha power, and how functional ability may associate with attentional control during audiovisual integration.

Author note: *The study hypotheses, design and statistical analyses were pre-registered online on the Open Science Framework: https://doi.org/10.17605/OSF.IO/J3VPF. This manuscript was prepared in collaboration with Dr Bo Yao, Dr Jason Braithwaite, Dr Theodoros Bampouras, and Dr Helen Nuttall.*

4.2. Abstract

The increased multisensory integration and weaker attentional control experienced by older adults during audiovisual processing can result in inaccurate perceptions of their dynamic, everyday environment. Crucially, these inaccurate representations of our environment can contribute to increased fall risk in older adults. A neural correlate of the attentional difference between younger and older adults could be oscillatory alpha activity (8-12Hz), indexing inhibitory processes during multisensory integration. The current study investigated whether age-related changes in alpha activity underlie weaker attentional control in older adults during a multisensory task, and if alpha associates with fall risk.

Thirty-six younger (18-35 years old) and thirty-six older (60-80 years old) adults completed a cued-spatial-attention stream-bounce task, assessing audiovisual integration when attending to validly-cued or invalidly-cued locations, at 0ms or 300ms stimulus-onset asynchronies. Oscillatory alpha activity was recorded throughout using EEG to index participants' inhibitory abilities. Functional ability and balance were measured to index fall risk.

Multiple linear regression models revealed that even when attending to the validly-cued location, less accurate multisensory integration was exhibited by older adults compared to younger adults; this suggests that older adults demonstrate weaker top-down modulation of multisensory integration through failing to inhibit task-irrelevant information. However, alpha power across the trials did not predict the extent of multisensory integration within the task. Crucially, a significant interaction between age and functional ability scores predicted alpha power, suggesting that older adults may rely on attentional mechanisms for functional ability more than younger adults do. Potential implications and applications of this in the design of clinical treatments to reduce fall risk are discussed.

Abstract word count: 258

Key words: ageing, alpha, attention, balance, falls, multisensory

4.3. Introduction

By 2050, it is expected that over 20% of the UK population will be 60 years old or above, with approximately 30% of community-dwelling adults over 65 suffering from falls (Zhang et al., 2020; Office for Health Improvement & Disparities, 2022). Falls have serious consequences on both an individual level and a systemic level – not only are they the most common cause of death for adults over 65, but also it is estimated that injuries associated with falls cost the National Health Service over £4.4 billion per year (Office for Health Improvement & Disparities, 2022). It is therefore highly important to understand the multifaceted causes of falls, including the age-related changes in perceptual and cognitive processes that may contribute to weaker functional ability and increased fall risk.

One potential reason behind increased fall risk in older adults are the age-related changes in multisensory integration. Multisensory integration describes the perceptual and cognitive mechanisms involved in binding sensory information together, to form a unitary percept of a person's body and environment (Stevenson et al., 2012; Talsma et al., 2010; Stein & Wallace, 1996; Diederich & Colonius, 2004). Research suggests that older adults display increased multisensory integration relative to younger adults (Pepper et al., 2023; Pepper & Nuttall, 2023; Laurienti et al., 2006; Peiffer et al., 2007; Mahoney et al., 2011). This increased integration has a positive outcome when the sensory information is congruent and should be integrated. For example, effectively utilising visual and auditory cues improves driving performance (Ramkhalawansingh et al., 2016) and speech perception abilities (see Jones & Noppeney, 2021, for a review). On the other hand, when task-irrelevant or incongruent information is erroneously integrated, this can have a negative outcome, producing representations of the environment that are confusing, noisy, and unstable (de Dieuleveult et al., 2017; Bedard & Barnett-Cowan, 2016). As such, the term "increased integration" refers to the erroneous binding of visual and auditory inputs that do not occur at the same time, or that is irrelevant to the task at hand.

Age-related changes in attentional control during audiovisual perception may be an underlying mechanism behind the increased multisensory integration experienced by older adults. Attentional mechanisms facilitate the processing of reliable, task-relevant sensory inputs and inhibit/filter the processing of task-irrelevant stimuli (Pepper et al., 2023; Pepper & Nuttall, 2023; Mozolic et al., 2008; Posner & Driver, 1992; Talsma et al., 2007). Older adults find it more difficult than younger adults to initiate top-down processes against irrelevant information and hence inhibit task-irrelevant information (Zhuravleva et al., 2014; Gazzaley et al., 2005), such as ignoring background noise when trying to focus on target speech; this has been termed the *'inhibitory deficit hypothesis'* (Hasher & Zacks, 1988; Alain & Woods, 1999). Indeed, after implementing the cued-spatial-attention stream-bounce task, Pepper et al. (2023) concluded that older adults found it more difficult than younger adults to segregate and inhibit the task-irrelevant auditory information from being integrated with the task-relevant visual information. Older adults displayed weaker attentional control during audiovisual integration, resulting in a less accurate multisensory performance compared to younger adults.

One possible candidate mechanism for the age-related changes in attentional control during audiovisual integration may be the deployment of neural alpha oscillations. Despite historically being referred to as an "idling" rhythm associated with resting brain areas (Pfurtscheller et al., 1996; Lange et al., 2015), oscillatory alpha activity is now considered to index top-down attention (Bednar & Lalor, 2018; Wostmann et al., 2017; Sauseng et al., 2005;

Capotosto et al., 2012; Thut et al., 2006) and active inhibitory processes during sensory processing (Klimesch et al., 2012; Foxe et al., 1998). Crucially, increases in alpha power over parieto-occipital areas are associated with inhibition of sensory information, preventing it from being integrated into the percept (Keller et al., 2017; Keil & Senkowski, 2017). For example, O'Sullivan et al. (2019) found that during audiovisual speech perception, when the visual information was incongruent and had to be inhibited, alpha power increased in parieto-occipital brain regions. Increases in alpha power suppressed the processing of distracting sensory inputs, to prevent the integration of incongruent auditory and visual information (Kelly et al., 2006; O'Sullivan et al., 2019). At this point, it is important to note that much of the research into the functional role of oscillatory alpha activity has been conducted on younger adult participant groups; the increased difficulty that older adults have in ignoring distracting, irrelevant sensory information (Zhuravleva et al., 2014; Gazzaley et al., 2005) may be reflected in reduced alpha power compared to younger adults during a multisensory task in which irrelevant sensory information must be inhibited.

Understanding more about the age-related changes in the attentional modulation of multisensory integration is key given our increasingly ageing population. Specifically, erroneous multisensory integration is associated with increased risk of falls in older adults (Setti et al., 2011; Stapleton et al., 2014; Mahoney et al., 2014; Peterka, 2002), as binding together task-irrelevant or incongruent sensory inputs can result in increased distractibility and inaccurate processing of relevant endogenous/exogenous stimuli (Poliakoff et al., 2006; Setti et al., 2011). An indicator of fall risk is the functional ability level of older adults; functional ability is often measured using composite assessments of balance ability, leg strength and gait speed. Strong functional ability is crucial for independence with healthy ageing, allowing older adults to move around the house, walk across the road, climb the stairs and perform other activities of daily living without being at a significant risk of falls (Dewhurst & Bampouras, 2014). Not only is functional ability challenged by age-related musculoskeletal declines, but it can also be significantly impacted by the weaker inhibitory control of older adults (Kahya et al., 2019). Crucially, due to their weaker attentional filtering, task-irrelevant sensory information is incorporated into older adults' representations of their environment, which could provoke distractibility and lead to a fall (Setti et al., 2011). It follows that if older adults are at an increased risk of falls compared to younger adults, this may be reflected in age-related differences in alpha activity during the attentional modulation of multisensory integration, in which distracting sensory information must be suppressed.

The aims of this study were to 1) investigate the role of parieto-occipital alpha power in age-related changes in audiovisual integration, and 2) investigate the association between audiovisual integration and functional ability. Younger and older participants completed the cued-spatial-attention version of the stream-bounce task as described in Pepper et al. (2023), whilst their alpha power was extracted from parieto-occipital regions. Participants' functional ability levels were also assessed. We tested the following hypotheses:

1) older adults will exhibit increased audiovisual integration compared to younger adults.

2) older adults will demonstrate weaker attentional control during audiovisual integration compared to younger adults.

3) older adults will demonstrate smaller increases from baseline in alpha power compared to younger adults.

4) balance ability will predict increased audiovisual integration and weaker attentional control during audiovisual integration

This experiment was pre-registered prior to data collection on Open Science Framework: https://doi.org/10.17605/OSF.IO/J3VPF

4.4. Methods

4.4.1. Participants

This study included a total of 72 participants; 36 younger adults (20 males, 16 females) between 18-35 years old (*M* = 22.67, *SD* = 4.09) and 36 older adults (14 males, 22 females) between 60-80 years old (*M* = 66.86, *SD* = 4.43). This sample size was determined via an a-priori power analysis using the pwr package in R studio (see pre-registration on Open Science Framework: https://doi.org/10.17605/OSF.IO/J3VPF). Specifically, the pwr.f2.test function was implemented as recommended for multiple regression/general linear model analyses (Kabacoff, 2015), using the large effect size generated by Pepper et al. (2023) and Kelly et al. (2006), a numerator degrees of freedom of 14, an alpha significance level of 0.05 and a power of 80%.

Participants were eligible for the study if they considered themselves fluent English speakers with normal or corrected-to-normal vision, screened for via self-report. Participants were ineligible to participate if they had a history or current diagnosis of cognitive impairments or neurological conditions (e.g. epilepsy, mild cognitive impairment, dementia, Parkinson's Disease) or learning impairments (e.g. dyslexia). Participants were also ineligible to participate if they had moderate-severe hearing loss resulting in the wearing of hearing aids; if they suffered from motion sickness; if they were diagnosed with any vestibular impairments (e.g. vertigo) or numbness in the lower limbs; if they were diagnosed with any muscle or bone conditions which could prevent standing comfortably (including lower limb, hip or spine surgery within the last year, or recent injury); if they relied on assistive walking devices (e.g. canes or walking frames), or if they were on medication which depresses the nervous system or affects balance (Thomas et al., 2016).

Participants were recruited via opportunity sampling; younger participants were students at Lancaster University, whilst older participants were recruited through the Centre for Ageing Research at Lancaster University; through advertising to local community groups, such as University of the Third Age; or through word of mouth. All participants provided informed consent. Ethical approval was received from Lancaster University Faculty of Science and Technology Ethics Committee (ref: FST-2022-0636-RECR-3).

4.4.2. Pre-screening tools

Participants were asked to complete two pre-screening questionnaires using Qualtrics online platform (Qualtrics XM, Provo, UT), to assess their eligibility for the study prior to coming to the lab.

Speech, Spatial and Quality of Hearing Questionnaire (SSQ; Appendix A; Gatehouse & Noble, 2004).

Participants rated their hearing ability in different acoustic scenarios using a sliding scale from 0-10 (0="Not at all", 10="Perfectly"). Whilst, at present, no defined cut-off score on the SSQ is available as a parameter to inform decision-making, previous studies have indicated that a mean score of less than 5.5 is indicative of moderate hearing loss (Gatehouse & Noble, 2004). As a result, people whose average score on the SSQ was lower than 5.5 were not eligible to participate in the experiment. This was to ensure that any changes in audiovisual integration measured in the task would not be due to a participant's inability to hear the auditory stimuli. Hearing acuity was then evaluated objectively using pure-tone audiometry when participants attended the lab.

Informant Questionnaire on Cognitive Decline in the Elderly (IQ-CODE; Appendix B; Jorm, 2004).

Participants used a self-report version of the IQ-CODE to rate how their performance in certain tasks has changed compared to 10 years ago, answering on a 5-point Likert scale (1="Much Improved", 5="Much worse"). An average score of 3.65 is the usual cut-off point when evaluating cognitive impairment and dementia (Slade et al., 2023; Jansen et al., 2008), therefore people whose average score was higher than 3.65 were not eligible to participate in the experiment. This was to ensure that any changes in audiovisual integration measured in the task would not be due to the participant experiencing mild cognitive impairment.

Pure-Tone Audiometry

If the online SSQ and IQCODE pre-screening questionnaires deemed the participants eligible for the study, they were invited to the lab for the in-person testing session. Pure-tone thresholds were measured bilaterally at 0.25 kHz, 0.5 kHz, 1 kHz, 2 kHz, 4 kHz and 8 kHz, in accordance with the British Society of Audiology (2018) guidelines. Pure tone average thresholds were averaged across 0.5-4kHz in each ear, and then averaged across ears. Audiometry was used to ensure that any differences in multisensory performance were not due to moderate-severe hearing loss. The mean pure-tone audiometry thresholds for each age group are displayed in *Figure 1.*

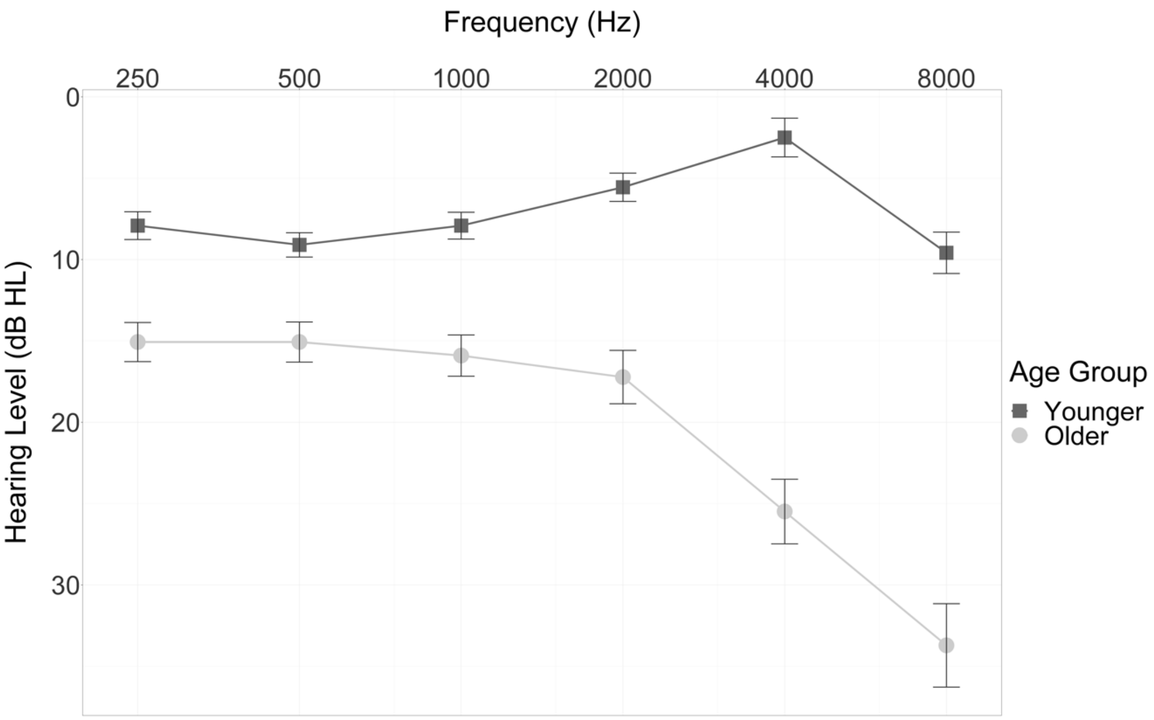


Figure 1. Mean pure-tone audiometry thresholds recorded for each age group at each frequency. Black markers represent data of younger adults, grey markers represent the data of older adults. Standard error displayed as error bars.

The mean scores of eligible participants in each pre-screening assessment are summarised in *Table 1*. Independent *t*-tests revealed there was no significant difference between age groups on the SSQ [$t(70) = -0.92$, $p=.154$; $M_{\text{Younger}} = 8.43$, $M_{\text{Older}} = 8.64$]. Older adults scored significantly higher score on the IQ-CODE questionnaire compared to younger adults [$t(70) = -11.50$, $p<.001$; $M_{\text{Younger}} = 1.96$, $M_{\text{Older}} = 3.07$]. Older adults had significantly higher PTA thresholds compared to younger adults [$t(70) = -8.16$, $p<.001$, $M_{\text{Younger}} = 6.27$, $M_{\text{Older}} = 18.30$].

Table 1

Mean scores on the *Speech, Spatial and Quality of Hearing Questionnaire* (SSQ), *Informant Questionnaire on Cognitive Decline in the Elderly* (IQ-CODE) and pure-tone audiometry (PTA) pre-screening measures, for both younger and older adults. Data is presented as mean (SD). Significance was set at a p<0.05.

Test	Younger	Older	*p*-value
SSQ	8.43 *(0.91)*	8.64 *(1.09)*	*p*=.154
IQCODE	1.96 *(0.55)*	3.07 *(0.19)*	***p*<.001**
PTA	6.27 *(4.56)*	18.30 *(7.59)*	***p*<.001**

4.4.3. Experimental Design

Questionnaire Measures

After passing the pre-screening eligibility assessments, all participants completed two self-report assessments of physical activity, providing detailed information regarding participants' own perception of their balance abilities and their fitness levels.

Activities-Based Balance Confidence Scale (ABC; Appendix C; Powell & Myers, 1995). The ABC scale is a 16-item questionnaire used to assess participants’ balance confidence in performing daily activities. Participants were asked to rate how confident they are in performing each activity, on a 10-point scale ranging from 0% (not confident at all) to 100% (completely confident). An average score of greater than 80% indicates high levels of functioning; a score of between 50% and 80% indicates moderate levels of functioning; a score of less than 50% indicate low levels of functioning. Crucially, a score of less than 67% is indicative of a substantial risk of falling.

Rapid Assessment of Physical Activity (RAPA; Appendix D; Topolski et al., 2006). RAPA is a 9-item questionnaire used to assess the level of physical activity in our participants. Participants are asked to answer Yes/No to whether the physical activity level in the scenario accurately describes them. The scale is divided into two parts. RAPA1 consists of 7 items and measures cardio-respiratory, aerobic activity. The highest affirmative score provided by participants is their final recorded score for RAPA1 (scored as 1 = "Sedentary", 2 = "underactive", 3 = "underactive regular - light activities", 4 and 5 = "underactive regular", 6 and 7 = "Active"). RAPA2 consists of 2 items and measures strength and flexibility-based physical activity. An affirmative response to the first item results in a score of 1; an affirmative response to the second item results in a score of 2; affirmative responses to both items scores 3; negative responses to both items scores 0. Participants' scores on RAPA1 and RAPA2 were added together to provide an overall indication of physical activity levels of the samples. Higher total scores represent higher levels of physical activity.

Functional Ability – The Short Physical Performance Battery (SPPB; Guralnik et al., 1994, 2000).

The SPPB is divided into three sections measuring balance, gait speed and leg strength, each of which are scored from 0-4 and added together to provide a composite measure of functional ability. As a result, the minimum score on the SPPB was 0 points and the maximum score was 12 points. Lower scores on the SPPB are indicative of weaker lower-body functioning and an increased risk of falls (Guralnik et al., 2000).

To increase the sensitivity of the data collected in these physical assessments, force platforms were implemented during the standing balance stage of the SPPB. Participants were asked to stand on force platforms with feet side-by-side, in a semi-tandem position, and in a tandem position, for 10 seconds each (if able to). Force platforms (PASCO, Roseville, CA, USA) collected centre of pressure movements in the anteroposterior and mediolateral axis, which were used to calculate sway area and sway velocity in each of the stance conditions. The force platforms were positioned side by side, without touching each other and recorded at a rate of 100Hz. Participants were asked to keep their hands by their sides throughout each assessment and focus on the wall ahead of them. Sway area and sway velocity values from the three stances were averaged and used for further analysis. SPPB scores were therefore considered to be measures of overall functional ability, whilst the sway measures extracted during the SPPB were considered to be measures of balance specifically.

Timed Up and Go Test (TUG; Podsiadlo & Richardson, 1991; Shumway-Cook et al., 2000)

As an additional dynamic measure of functional ability, participants were also asked to complete the Timed Up-And-Go (TUG) test, which is a clinical assessment of fall risk in older adults. Participants are asked to stand from the chair, walk 3 metres at a comfortable pace, turn around, walk back to the chair and sit down. The time that participants took to complete this assessment was recorded, with longer times (greater than 13.5 seconds for community-dwelling older adults; Shumway-Cook et al., 2000) indicating increased fall risk.

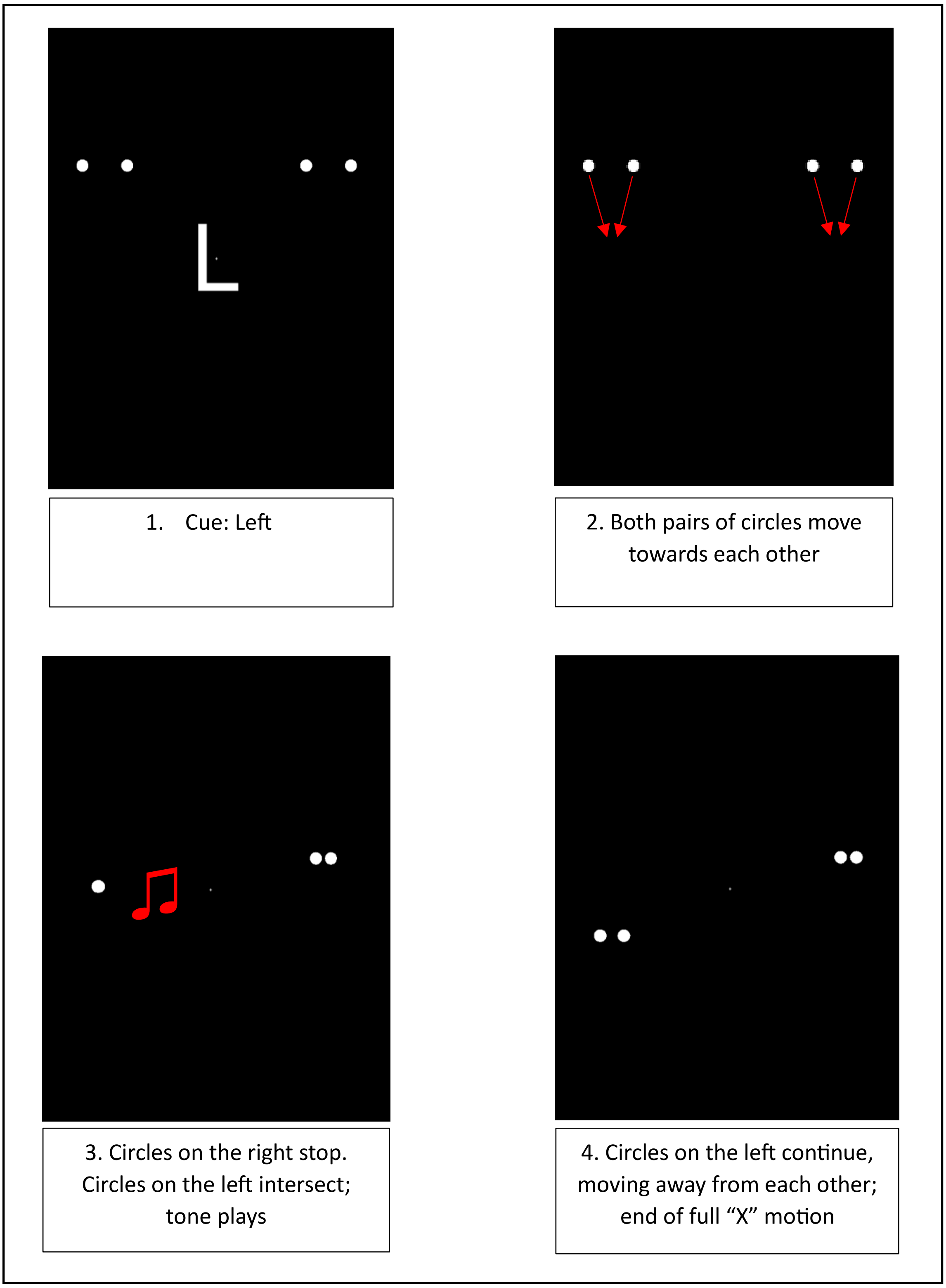
The Stream-Bounce Task

This behavioural task implemented a 2 (Age: Younger vs Older) x 2 (Cue: Valid vs Invalid) x 3 (Stimulus Onset Asynchrony [SOA]: Visual Only [VO] vs 0 milliseconds vs 300 milliseconds) mixed design, with Age as a between-subjects factor and Cue and SOA as within-subjects factors.

The stream-bounce stimuli used in the task were replicated from Donohue et al. (2015), with experimental details described previously in Pepper et al. (2023). Briefly, at the start of each trial, participants focused on a fixation cross for 1 second. Participants were then cued either towards the full "X" shaped motion of the stimuli (validly-cued trials) or towards the stopped motion of the stimuli (invalidly-cued trials) appearing on the computer screen. Two thirds of the trials contained a task-irrelevant sound, played either synchronously with the circles intersecting (0ms delay) or 300ms afterwards. The remaining trials were visual-only. At the end of each trial, participants were asked whether they perceived the circles to "pass through" or "bounce off" each other.

The experiment consisted of 12 different trial conditions, randomised across all participants. The experimental block contained of a set of 60 validly-cued trials and a set of

60 invalidly-cued trials (two conditions), which were equally distributed between each side of the screen (left/right) and three stimulus onset asynchrony (SOA) conditions (Visual Only [VO], 0 milliseconds and 300 milliseconds); this means that each participant completed 120 valid trials and 120 invalid trials for each SOA. Participants completed the experiment in a quiet room on an Apple Mac computer (version 12.2.1) with a standard keyboard. All participants wore EEG-compatible earphones (ER2 ultra-shielded insert earphones; Intelligent Hearing Systems). A volume check was conducted at the beginning of the experiment; participants were presented with a constant tone and the volume of this tone was adjusted to a clear and comfortable level. Screen captures of a validly-cued, 0ms SOA trial are displayed in *Figure 2.* The percentage of “Bounce” responses provided in each Cue x SOA condition was calculated for each participant.



1. Cue: Left

2. Both pairs of circles move towards each other

3. Circles on the right stop. Circles on the left intersect; tone plays

4. Circles on the left continue, moving away from each other; end of full “X” motion

Figure 2. Screen captures of a validly-cued trial (valid left), with an SOA of 0ms (sound synchronous with intersection). Participants provided their pass/bounce judgement at the end of the trial. Image taken from the published manuscript of Pepper et al. (2023).

4.4.4. EEG Data Acquisition and Pre-Processing

Continuous EEG data were sampled at 500Hz from a 32-channel EEG amplifier system (BrainAmps, BrainProducts GmbH, Germany) with Ag/AgCl electrodes positioned according to the international 10-20 system (actiCAP EasyCap, BrainProducts, GmbH, Germany), referenced to the central Reference electrode during recording. The data underwent online bandpass filtering, applying a low cut-off filter of 0.1Hz, a high-cut-off filter of 40Hz, and a notch filter of 50Hz. Psychopy and BrainVision Recorder (version 1.10, Brain Products GmbH, Germany) were used in conjunction to record trial-specific information in real time, including EEG triggers coded to identify the condition each participant experienced and when the participant provided a key press response (Franzen et al., 2020; Klatt et al., 2020). These data were collected and stored for offline analysis in EEGLAB.

Processing and EEG analyses were completed offline using the EEGLAB toolbox (Delorme & Makeig, 2004) and MATLAB scripts. The EEG data was first resampled to 256Hz and re-referenced to the average of all electrodes. Breaks between experimental blocks were removed and an independent component analysis (ICA) was performed on the data. Artefactual independent components were detected and rejected using the ICFlag function in EEGLAB; components that were identified as being over 80% likely to be heart, muscle or eye artefacts were removed from the dataset (Delorme et al., 2007). The pre-processed EEG data were then epoched, beginning at the presentation of the fixation cross in the stream-bounce task and ending 3 seconds afterwards once the circles had completed their full motion.

Alpha power extraction

Alpha power was extracted from the 8-12Hz frequency band at electrodes positioned over the parietal and occipital lobes (P3, P4, P7, P8, O1, O2, Oz). The use of parieto-occipital electrodes is in line with previous research investigating posterior alpha activity for audiovisual integration (Getzmann et al., 2020; O'Sullivan et al., 2019; van Driel et al., 2017; Thut et al., 2006; Klatt et al., 2020). Alpha power was determined using the power spectral density (PSD) package in EEGLAB. The 'spectopo' function is based upon Welsch's method and uses a 256-point Hamming window. Within each epoch, for each participant, mean alpha power over each electrode was calculated for the 1000ms pre-stimulus interval of each condition type, and for the 2000ms stream-bounce trial of each condition type. The alpha power was then averaged across all electrodes of interest, to produce a grand mean alpha power value for the experimental condition, and a grand mean alpha power for the pre-stimulus baseline associated with each condition. Mean baseline alpha power was then subtracted from mean experimental alpha power to produce an alpha power value representative of the difference in alpha power between ‘rest’ (pre-stimulus interval) and the experimental trial.

4.4.5. Procedure

The procedure outlining the entirety of the study is displayed in *Figure 3*.

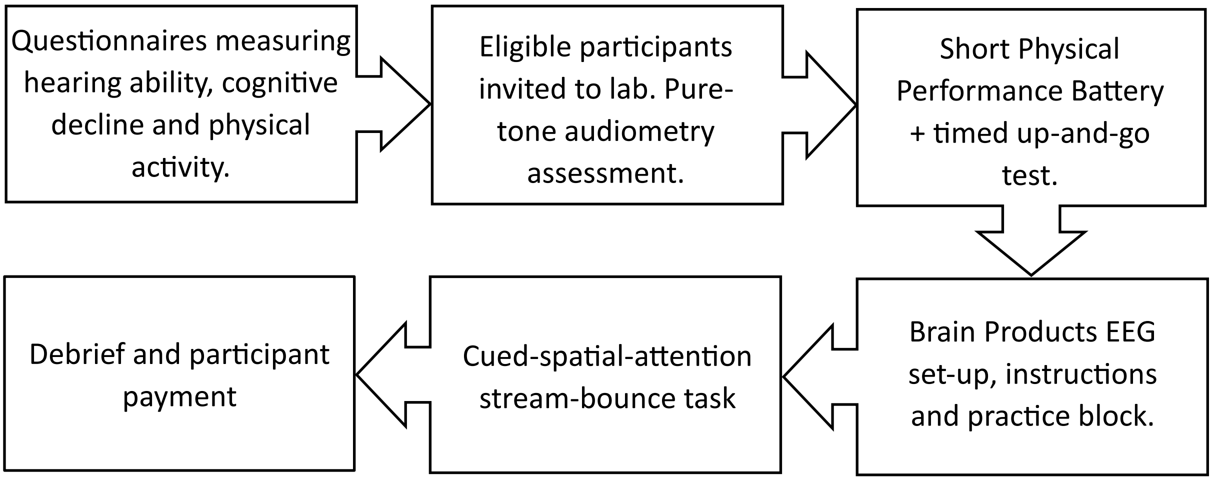


Figure 3. Flowchart detailing the procedure of the study.

4.4.6. Statistical Analyses

Two multiple linear regression models were run to examine whether a) age, oscillatory alpha power and balance ability and the interactions of each variable with age can predict audiovisual integration in the stream-bounce task (Model 1: Proportion of "Bounce" responses = Age + Cue + SOA + Alpha power difference + Sway Velocity + SPPB Score + Pure-tone audiometry + Age*Cue + Age*Alpha + Age*Velocity + Age*SPPB Score), and b) age, audiovisual integration and balance ability and the interactions of each variable with age can predict oscillatory alpha power (Model 2: Alpha power difference = Age + Cue + SOA + Proportion of "Bounce" responses + Sway Velocity + SPPB Score + Pure-tone audiometry + Age*Cue + Age*Bounce + Age*Velocity + Age*SPPB Score). Prior to the examination of the models, the variables were assessed for violation of the related assumptions; the assessment confirmed that all relevant assumptions were met. To correct for multiple models, all regression analyses were conducted using an alpha value of p=.025 and the adjusted values are reported. To address the violation of ANOVA assumptions present with the "Bounce" percentage data (i.e. bound data), these grand means were converted into z-scores, following the procedures recommended by Caldwell et al. (2019). Data were analysed and visualised in R Studio (version 4.2.1) using the 'stats' (R Core Team, 2022), 'car' (Fox & Weisberg, 2019), 'performance' (Ludecke et al., 2021), 'emmeans' (Lenth, 2023) and 'ggplot2' (Wickham, 2016) packages. Post-hoc ANOVAs and correlational analyses were used to analyse the differences and relationships between conditions and age groups. Pure-tone audiometry thresholds were included within each model to control for any age-related differences in hearing ability.

4.4.7. Deviations from pre-registration

In the pre-registration for this study, it was proposed to include the TUG test times in both models as a measure of functional ability. However, as is indicated by the very high ABC and RAPA scores (see *Table 4* in *Results*), the older adult sample in this study were very physically able. As a result, the TUG test is not likely to be sensitive enough to detect fall risk in these active older adults (Barry et al., 2014), while not allowing separation of the different elements that contribute to its performance. Given that the SPPB can also be used as a measure of functional ability, while the distinct and distinguishable measures it comprises of allows direct assessment of balance, it was deemed unnecessary to include both the SPPB and the TUG in the model. As such, and after finding moderate collinearity between Sway Area and Sway Velocity during model checks, Sway Area and Timed Up-And-Go times were omitted as model predictors.

4.5. Results

4.5.1. H1: Older adults will exhibit increased audiovisual integration compared to younger adults

The mean proportion of “Bounce” responses within each condition, for each age group, are displayed in *Figure 4*.

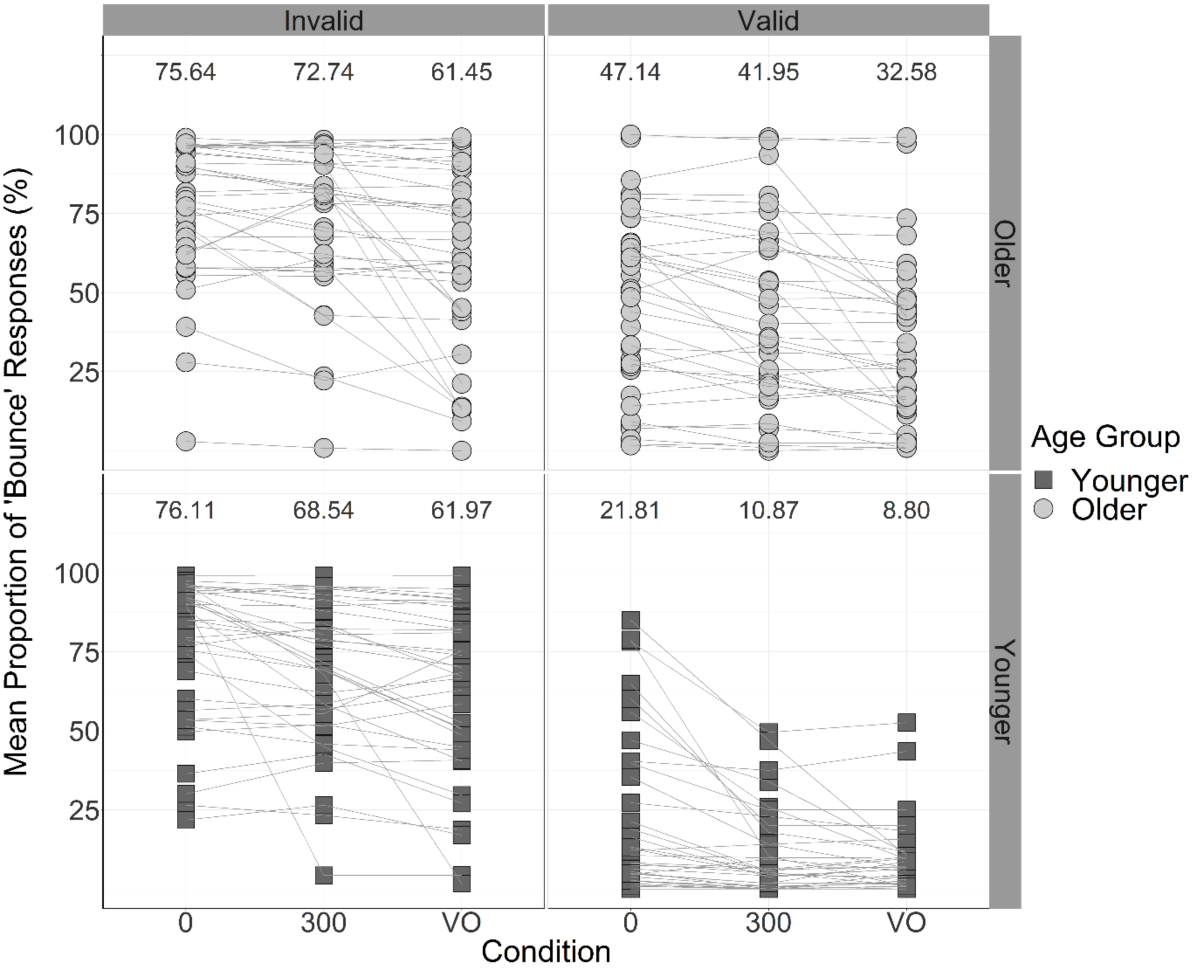


Figure 4. Mean proportion of “Bounce” responses in each Cue and SOA condition for each participant. Bottom panels represent data of younger adults, top panels represent the data of older adults. Participants’ “Bounce” responses are linked across conditions using lines. Numbers at the top of each panel display the mean proportion of “Bounce” responses in each condition.

For Model 1, the outcome was the proportion of "Bounce" responses produced in the stream-bounce task. The model was significant overall [F(12,413) = 36.47, p<.001, adjusted $R^2 = 0.50$].

The output from the ANOVA performed on the multiple regression model is displayed in Table 2.

Table 2

Multiple linear regression output detailing the statistical contribution of each prediction and interaction to the outcome of the proportion of "Bounce" responses.

Full Model: Bounce = Age + Cue + SOA + Alpha + Velocity + SPPB Score + PTA + Age*Cue + Age*Alpha + Age*Velocity + Age*SPPB Score

Predictors	Df	Sum of squares	Mean square	*F value*	*p*	*Adjusted p-value*
Age Group	**1**	**16.64**	**16.64**	**33.33**	**<.001**	**<.001**
Cue	**1**	**167.26**	**167.26**	**335.01**	**<.001**	**<.001**
SOA	**2**	**12.31**	**6.16**	**12.33**	**<.001**	**<.001**
Alpha	1	0.06	0.06	0.11	0.741	1.00
Sway Velocity	1	1.97	1.97	3.95	0.048	0.095
SPPB Score	1	2.48	2.48	4.96	0.026	0.053
PTA	1	0.15	0.15	0.29	0.589	1.00
Age*Cue	**1**	**15.79**	**15.79**	**31.63**	**<.001**	**<.001**
Age*Alpha	1	0.02	0.02	0.05	0.830	1.00
Age*Velocity	1	1.29	1.29	2.59	0.108	0.217
Age*SPPB Score	1	0.55	0.55	1.09	0.296	0.592
Residuals	413	206.20	0.50			

Notes: Df = degrees of freedom; SOA = Stimulus-Onset Asynchrony; SPPB = Short Physical Performance Battery; PTA = pure-tone audiometry

With regards to the individual predictors in the model, there was a significant main effect of Age on the proportion of "bounce" responses [*F*(1, 413) = 33.33, *p*<.001]. Overall, a significantly greater proportion of "bounce" responses were produced by older adults (*M* = 55.25%, *SE* = 2.21, 95% CI [50.85, 59.65]) than by younger adults (*M* = 41.35%, *SE* = 2.21, 95%

CI [36.95, 45.75]; mean difference = 13.90%, *SE* = 3.12, 95% CI [7.68, 20.12]), providing support for hypothesis one which predicted that older adults will exhibit increased audiovisual integration compared to younger adults.

4.5.2. H2: Older adults will demonstrate weaker attentional control during audiovisual integration compared to younger adults.

The interaction between Age and Cue was a significant predictor of "Bounce" responses [*F*(1, 413) = 31.63, *p*<.001]. To analyse pairwise comparisons within the Age and Cue interaction, the “bounce” responses in each SOA condition were collapsed, so that a mean percentage of “bounce” responses provided by each participant could be calculated for validly cued and invalidly cued conditions. These percentages were then converted to standardized z-scores.

Age pairwise comparisons. To assess differences between the proportion of “bounce” responses provided by younger adults and older adults in valid trials, and the differences between younger and older adults in invalid trials, two separate one-way ANOVAs were conducted. The first one-way ANOVA analysed responses in the valid condition, and revealed that there were significant differences in the proportion of “bounce” responses between age groups, [*F*(1, 70) = 27.61, *p* < .001]. In the valid condition, a significantly greater proportion of “bounce” responses were produced by older adults (*M* = 40.56%, *SE* = 4.39, 95% CI [31.64, 49.47]) than younger adults (*M* = 13.83%, *SE* = 2.57, 95% CI [8.61, 19.04]). This provides support for hypothesis two, suggesting that even in the validly-cued conditions, older adults still integrated the visual and auditory information more frequently than younger adults, displaying weaker attentional filtering.

The second one-way ANOVA analysed responses in the invalid condition, and in contrast, indicated no significant difference between age groups, [*F*(1, 70) = 0.04, *p* = .839]. In the invalid condition, a similar proportion of “bounce” responses were produced by younger adults (*M* = 68.87%, SE = 3.62, 95% CI [61.52, 76.23]) and by older adults (*M* = 69.94%, *SE* = 3.78, 95% CI [62.27, 77.61]).

Cue pairwise comparisons. To assess differences in the proportion of “bounce” responses provided by younger adults in valid versus invalid trials, and by older adults in valid versus invalid trials, a repeated-measures ANOVA was conducted on the collapsed z-score data. When examining the data of younger adults, there was a significant difference in the proportion of “bounce” responses in validly cued and invalidly cued trials, [*F*(1, 35) = 155.44, *p* < .001, η_p^2 = 0.82]. Overall, younger adults produced a significantly greater proportion of “bounce” responses in invalidly cued trials (*M* = 68.87%, *SE* = 3.62, 95% CI [61,52, 76.23]) compared with validly cued trials (*M* = 13.83%, *SE* = 2.57, 95% CI [8.61, 19.04]; mean difference = 55.05%, *SE* = 4.42). When examining the data of older adults, there was also a significant difference in the proportion of “bounce” responses in the validly cued and invalidly cued trials, [*F*(1, 35) = 17.93, *p* < .001, η_p^2 = 0.34]. Overall, older adults produced a greater proportion of “bounce” responses in the invalid trials (*M* = 69.94%, *SE* = 3.78, 95% CI [62.27, 77.61]) compared to valid trials (*M* = 40.56%, *SE* = 4.39, 95% CI [31.64, 49.47]; mean difference = 29.39%, *SE* = 6.94).

4.5.3. *H3: Older adults will show smaller increases from baseline in alpha power compared to younger adults.*

For Model 2, the outcome was the difference in alpha power from baseline in the experimental trials of the stream-bounce task. The model was significant overall [*F*(12,413) = 2.03, *p*=.021, adjusted R^2 = 0.03]. There were no significant main effects in the model, and the interactions between age and cue, age and "bounce" responses and age and velocity were not significant. As a result, the data did not support hypothesis three that alpha power would reflect age-related changes in attentional control during multisensory integration. However, there was a significant interaction between age and SPPB scores on alpha power [*F*(1, 413) = 17.29, *p*<.001]. The output of the ANOVA conducted on the multiple regression model is displayed in Table 3.

Table 3

Multiple linear regression output detailing the statistical contribution of each prediction and interaction to the outcome of alpha power.

Full Model: Alpha ~ Age + Cue + SOA + Bounce + Velocity + SPPB Score + Age*Cue + Age*Bounce + Age*Velocity + Age*SPPB Score

Predictors	Df	Sum of squares	Mean square	*F value*	*p*	*Adjusted p-value*
Age Group	1	4.26	4.26	1.89	0.170	0.340
Cue	1	0.53	0.53	0.24	0.628	1.00
SOA	2	0.38	0.19	0.08	0.920	1.00
Bounce	1	0.23	0.23	0.10	0.747	1.00
Sway Velocity	1	0.37	0.37	0.16	0.686	1.00
SPPB Score	1	1.76	1.76	0.78	0.377	0.755
PTA	1	0.01	0.01	0.01	0.936	1.00

Age*Cue	1	0.05	0.05	0.02	0.882	1.00
Age*Bounce	1	0.70	0.70	0.31	0.578	1.00
Age*Velocity	1	7.51	7.51	3.33	0.069	0.756
Age*SPPB Score	**1**	**39.00**	**39.00**	**17.29**	**<.001**	**<.001**
Residuals	413	931.25	2.26			

Notes: Df = degrees of freedom; SOA = Stimulus-Onset Asynchrony; SPPB = Short Physical Performance Battery score; PTA = pure-tone audiometry threshold

4.5.4. H4: Balance will predict audiovisual integration and attentional control

After correcting p-values for multiple comparisons, there was no significant main effect of SPPB score on the proportion of "Bounce" responses [Model 1, Table 2; *F*(1, 413) = 4.96, *p*=.095]. In addition, after correcting p-values, there was no significant main effect of sway velocity on the proportion of "bounce" responses [*F*(1, 413) = 3.95, *p*=.053]. Taken together, the data did not support hypothesis four that weaker functional ability or balance ability would predict audiovisual integration within the stream-bounce task.

However, Model 2 (Table 3), indicated there was a significant interaction between age and SPPB scores on alpha power [*F*(1, 413) = 17.29, *p*<.001]. To analyse this interaction, correlational analyses were conducted, assessing the relationship between alpha power and SPPB scores in younger adults and in older adults. These exploratory correlational analyses revealed that for younger adults, there was a significant negative relationship between alpha power and SPPB scores [*r*(214) = -0.15, *p*=.025], with lower alpha power being associated with stronger functional ability. In contrast, for older adults, there was a significant positive relationship between alpha power and SPPB scores [*r*(214) = 0.20, *p*=.002], with higher alpha power being associated with stronger functional ability. Participants' SPPB scores are displayed in Figure 5.

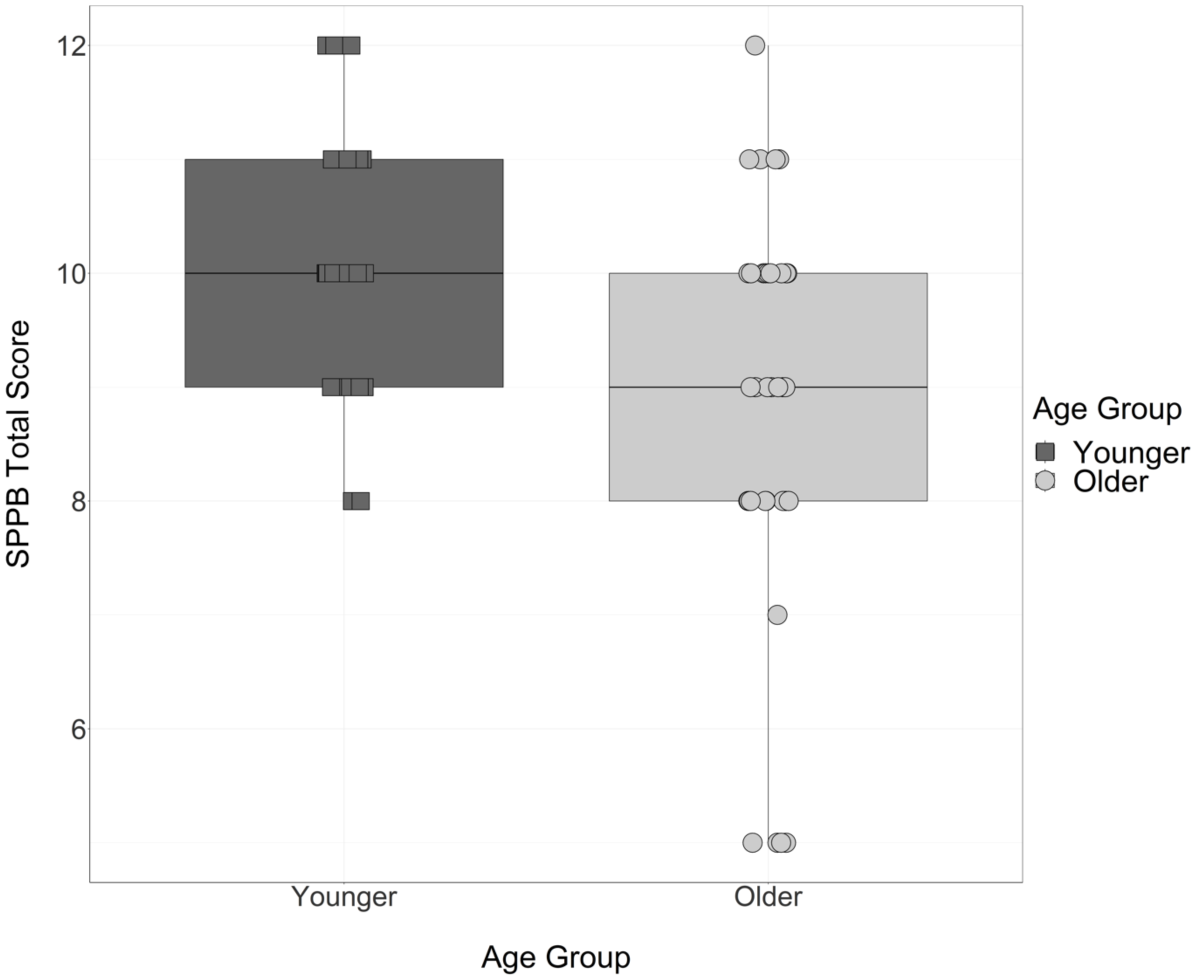


Figure 5. Short Physical Performance Battery scores for all participants. Black squares and boxplot represent data of younger adults, grey circles and boxplot represent the data of older adults. Each boxplot displays the median, the lower and upper quartile for each condition.

Exploratory analyses were also conducted to investigate differences between age groups for their subjective perspectives of their balance ability and physical activity levels, using the questionnaire data collected from participants before the testing session. The mean scores on the ABC and RAPA questionnaires are displayed in *Table 4.* An independent *t*-test revealed that there was no significant difference between age groups on the ABC [*t*(70) = 0.48, *p*=.995] or on total RAPA scores [*t*(70) = 0.63, *p*=.282].

Table 4

Mean scores on the ABC and RAPA self-report questionnaires on balance confidence and physical activity, for both younger and older adults. Standard deviations displayed in parentheses.

Age group	**ABC**	**RAPA1 (aerobic)**	**RAPA2 (strength)**	**ABC Class**	**RAPA Class**
Younger	95.10	5.67	1.42	High functioning	Underactive regular
	(9.61)	*(1.59)*	*(1.11)*		
Older	94.16	5.72	1.06	High functioning	Underactive regular
	(6.72)	*(1.16)*	*(1.24)*		

4.6. Discussion

The aims of this study were to 1) investigate the role of parieto-occipital alpha power in age-related changes in audiovisual integration, and 2) investigate the association between audiovisual integration and functional ability. Whilst results from the stream-bounce task provide support for the theory that older adults exhibit increased audiovisual integration and weaker attentional control compared to younger adults, oscillatory alpha power, functional ability and balance ability did not predict such changes. However, an interaction between participants' functional ability and age predicted alpha power within the task; this indicates younger and older adults may display a differential reliance on attentional mechanisms for functional ability.

Older adults displayed weaker attentional control during audiovisual integration compared to younger adults.

The finding that older adults produced a greater proportion of "Bounce" responses compared to younger adults, even when attending to the validly-cued location, is consistent with the results of Pepper et al. (2023) and supports our hypothesis. Despite the fact that participants were paying attention to the visual stimuli in the validly-cued condition, which should strengthen the ability to suppress the task-irrelevant sound, older adults integrated the sound and the visual intersection more frequently than younger adults did. This is in line with the inhibitory deficit hypothesis (Hasher & Zacks, 1988) – older adults found it more difficult to inhibit the distracting sound in the stream-bounce task and as a result, produced a greater proportion of "Bounce" responses, even if the sound occurred after the circles intersected.

This kind of erroneous multisensory integration exhibited by older adults has important consequences for their ability to safely perceive and navigate through dynamic environments, in that weaker top-down modulation of multisensory integration may result in the increased processing of irrelevant sensory information. It is important that future research investigates age-related changes in attentional control in relation to complex audiovisual stimuli that participants encounter in real-world environments (e.g. speech). This will allow researchers to arrive at more ecologically valid conclusions regarding the impact of older adults' increased integration and weaker attentional control on perception and action. The use of dynamic visual stimuli, however, is useful for studying the impact of age-related changes in audiovisual integration on fall risk, due to the importance of optic flow mechanisms, for example, in guiding safe locomotion and maintaining balance (Raffi & Piras, 2019; Peterka et al., 1995).

Oscillatory alpha power did not predict audiovisual integration.

The data in the current study did not provide support for our hypothesis – alpha power did not predict the proportion of "Bounce" responses produced in the stream-bounce task. A potential reason for this is that perhaps analysing alpha activity alone is insufficient for investigating the interplay between multisensory integration and inhibitory control (Talsma et al., 2010), especially when the moving stimuli used in this task are more complex than simple flashes and beeps. For example, whilst alpha activity appears to be crucial in top-down attentional control and inhibitory functioning, gamma activity (30-80Hz) is believed to reflect the bottom-up processing of low-level sensory inputs (Keil & Senkowski, 2018; Krebber et al., 2015; Scurry et al., 2021). Scurry et al. (2021) implemented the sound-induced flash illusion with younger, healthy older and fall-prone older adults, measuring their alpha and gamma activity throughout. The researchers found that fall-prone older adults were more susceptible to the sound-induced flash illusion, displaying increased integration and less accurate multisensory perception. Importantly, these fall-prone older adults displayed reduced phase-amplitude coupling between oscillatory gamma and alpha activity, indicative of less modulated multisensory integration compared to non-falling older adults. As such, whilst analysing power within individual frequency bands is useful for identifying the functional role of specific types of neural oscillations, it is likely that with regards to multisensory integration, more holistic findings may come from analysing the synchronisation of multiple neural oscillations to understand how information from different senses is selected and bound together (Scurry et al., 2021).

Age-related changes in functional ability predicted alpha power, but not audiovisual integration.

The interaction between functional ability and age group was found to predict alpha power within the task, which may provide support for the role of attentional control in the balance elements of functional ability. Not only is balance negatively affected by age-related challenges concerning musculoskeletal demands, medications causing dizziness and unisensory declines (Lim & Kong, 2022; Callis, 2016; Reed-Jones et al., 2013), but the weaker inhibitory abilities experienced by older adults is also a significant contributor to their increased risk of falls (Zhang et al., 2020).

Unpicking this significant interaction may lead to important insights into how younger and older adults employ attentional mechanisms for functional ability. That is, for younger adults, lower increases in alpha power from baseline (i.e. lesser inhibitory control) were associated with higher SPPB scores (i.e. stronger functional ability), which is surprising considering the role of attention and inhibition in the balance elements of functional ability. However, for older adults, greater increases in alpha power were associated with stronger functional ability (higher SPPB scores). Perhaps the reason for this difference lies in the age-related changes in the neural mechanisms relied upon for balance in each age group (Malcolm et al., 2021). Indeed, age-related declines in sensorimotor tracts within posture control loops result in the increased activation of cortical brain regions for balance maintenance in older adults (Pepper & Nuttall, 2023; Kahya et al., 2019; Malcolm et al., 2021; Ozdemir et al., 2018). For example, Ozdemir et al. (2018) found increased gamma activity in central, frontal and central-parietal areas of older adults when sensory information is compromised; these increases in gamma activity have previously been attributed to sustained attention (Slobounov et al., 2009). Ozdemir et al. (2018) postulated that older adults may allocate increased attentional resources to postural control than younger adults.

This is in line with the scaffolding theory of cognitive ageing (Reuter-Lorenz & Park, 2014; Oosterhuis et al., 2023), in which increased cortical activation may be a compensatory strategy for older adults to maintain functional ability despite neural degeneration of subcortical balance centres (Oosterhuis et al., 2023; Kahya et al., 2019; Park & Reuter-Lorenz, 2009; Montero-Odasso et al., 2017). In the context of the current study, older adults displaying an association between increased parieto-occipital alpha power and higher SPPB scores may support for the role of inhibitory processes in functional ability, and perhaps reflects the increased involvement of cortical regions for supporting functional ability in older adults. That is, in line with the "gating-by-inhibition" theories of alpha (Jensen & Mazaheri, 2010), the increased parieto-occipital alpha power in older adults may serve to increase the availability of cortical resources required for balance maintenance. In contrast, the negative relationship between alpha power and SPPB scores in younger adults may instead reflect the lesser role of inhibitory mechanisms for functional ability in this age group, whose sub-cortical sensorimotor tracts are intact, rendering balance a more automatic process. It is important that future research focusses on uncovering the age-related changes in the cortical mechanisms required for balance maintenance, as at the moment, the evidence into such changes appears to be limited (Malcolm et al., 2021; Ozedmir et al., 2018).

A potential reason as to why functional ability and balance ability did not predict audiovisual integration within the task (Model 1) could be that the older adults who participated in the study were very physically fit and able. This is evident in that the younger and older adults who participated in the current study displayed no significant differences in balance confidence (as measured by the Activities-Specific Balance Confidence scale) or in physical activity levels (as measured by the Rapid Assessment of Physical Activity). Whilst older adults may display increased audiovisual integration within the stream-bounce task, the high physical ability of these older adults may mask the effects that this less accurate integration has on their balance. As such, perhaps balance ability as measured in this study was not sensitive enough to predict age-related changes in audiovisual integration. Indeed, many clinical assessments of balance and fall risk appear to suffer from floor and ceiling effects and lack sensitivity to detect small changes in balance ability (Balasubmaranian, 2015; Rockwood et al., 2008; Yelnik & Bonan, 2008). The finding that participants' balance ability did not predict audiovisual integration within this task may also be a promising indication that whilst older adults may experience increased audiovisual integration, regular exercise and maintaining strong physical wellbeing could reduce the effects that these maladaptive perceptual changes have on fall risk in older adults.

Practical applications and future considerations

The roles of attention and inhibition in multisensory integration, and the weakening of cognitive abilities with healthy ageing, raises important questions regarding the treatments and therapies that could be designed to improve the integrative processes of older adults and reduce their risk of falls. That is, whilst strength and balance training has been proven to improve gait and thus potentially reduce fall risk in older adults during motor interventions (see Sherrington et al., 2008, for a detailed meta-analysis), the most effective programmes appear to come from combining physical and cognitive therapies (de Bruin et al., 2011; Pichierri et al., 2012; van het Reve & de Bruin, 2014), over a sustained period of time. For example, van het Reve & de Bruin (2014) implemented a combined motor and cognitive intervention with older adults, in which alongside an exercise programme, participants also received 12 weeks of cognitive training which included attending to task-relevant stimuli and suppressing task-irrelevant stimuli. The researchers found that after strength-balance-cognitive training, participants' dual task costs during walking were significantly reduced and gait initiation was improved compared to participants who underwent strength-balance training alone. Taken together, perhaps combined physical and cognitive treatments could be effective in reducing the risk of falls in older adults (van het Reve & de Bruin, 2014; Uemura et al., 2012). However, when randomised control trials have been implemented amongst community-dwelling older adults, the findings have been mixed with regards to whether combined cognitive and physical interventions can reduce fall risk more than physical therapy in isolation (Turunen et al., 2022; Lipardo & Tsang, 2020; Segev-Jacubovski et al., 2011). As such, it is clear that further research is needed, with larger sample sizes and more diverse older adult populations, to determine whether such combined treatments are effective in minimising risk of falls in older adults.

The sampling bias that may be present in many studies investigating age-related changes in balance maintenance, or indeed any physical or cognitive aspect of ageing, must be taken into account in future research. For example, Brayne & Moffitt (2022) explained how 'healthy volunteer bias' is a high occurrence within ageing research, with older adults who agree to participate in such studies often being from more affluent subsections of society and healthier than randomly selected sample of the population. A consequence of this is that the results from studies using particularly healthy and able older adult samples may not be representative of the entire older adult population, making it difficult to generalise the findings (Brayne & Moffitt, 2022). However, it is important to note that these kinds of healthy volunteer biases are not necessarily limitations of ageing research, but instead, more detailed information about participants' lifestyle, fitness, education and socialisation may be needed to create a more comprehensive account of the cognitive and physical abilities of the samples used – see Stern et al. (2020) and Oosterhuis et al. (2023) for reviews on the 'cognitive reserve' theories of ageing, which may contribute to the high level of individual differences within older adult groups.

4.7. Conclusion

To conclude, the weaker top-down modulation of multisensory integration in older adults can have serious implications for their perception of and navigation through their dynamic environment. This study has provided support for the role of attentional control in functional ability, with age-related deteriorations in inhibitory function being a potential contributor to the increased risk of falls in older adults. To determine the underlying neural correlates of age-related changes in the top-down and bottom-up mechanisms of multisensory integration, and how these affect fall risk, it may be important to analyse neural activity from multiple frequency bands, to understand how oscillations coordinate to support multisensory perception and action. Future research must also investigate the possibility of younger and older adults using different strategies in facilitating the processing of task-relevant information and inhibiting task-irrelevant information; each age group may rely upon different brain areas and different mechanisms to support multisensory integration, compensating for age-related neurodegeneration. Specifically, the increased activation of cortical brain regions in older adults is likely to reflect their increased reliance on attentional and inhibitory mechanisms for balance maintenance, compared to younger adults. Developing a detailed understanding of the age-related changes in multisensory integration, and how this may influence fall risk, could provide important direction for the design of cognitive treatments to sharpen the perception of older adults and improve their allocation of attentional resources during balance maintenance.

References

Alain, C., & Woods, D. L. (1999). Age-related changes in processing auditory stimuli during visual attention: evidence for deficits in inhibitory control and sensory memory. *Psychology and aging*, *14*(3), 507.

Balasubramanian, C. K. (2015). The community balance and mobility scale alleviates the ceiling effects observed in the currently used gait and balance assessments for the community-dwelling older adults. *Journal of geriatric physical therapy*, *38*(2), 78-89.

Barry, E., Galvin, R., Keogh, C., Horgan, F., & Fahey, T. (2014). Is the Timed Up and Go test a useful predictor of risk of falls in community dwelling older adults: a systematic review and meta-analysis. *BMC geriatrics*, *14*, 1-14.

Bedard, G., & Barnett-Cowan, M. (2016). Impaired timing of audiovisual events in the elderly. *Experimental brain research*, *234*(1), 331-340.

Bednar, A., & Lalor, E. C. (2018). Neural tracking of auditory motion is reflected by delta phase and alpha power of EEG. *NeuroImage*, *181*, 683-691.

Brayne, C., & Moffitt, T. E. (2022). The limitations of large-scale volunteer databases to address inequalities and global challenges in health and aging. *Nature Aging*, *2*(9), 775-783.

British Society of Audiology. (2018, August). *Recommended Procedure: Pure-tone air-conduction and boneconduction threshold audiometry with and without masking.* Available online: https://www.thebsa.org.uk/wp-content/uploads/2018/11/OD104-32-Recommended-Procedure-Pure-Tone-Audiometry-August-2018-FINAL-1.pdf

Caldwell, J. A., Niro, P. J., Farina, E. K., McClung, J. P., Caron, G. R., & Lieberman, H. R. (2019). A Z-score based method for comparing the relative sensitivity of behavioral and physiological metrics including cognitive performance, mood, and hormone levels. *Plos one*, *14*(8), e0220749.

Callis, N. (2016). Falls prevention: Identification of predictive fall risk factors. *Applied nursing research*, *29*, 53-58.

Capotosto, P., Babiloni, C., Romani, G. L., & Corbetta, M. (2012). Differential contribution of right and left parietal cortex to the control of spatial attention: a simultaneous EEG–rTMS study. *Cerebral cortex*, *22*(2), 446-454.

de Bruin, K. M. E. D., Pichierri, G., & Wold, P. (2011). Cognitive and cognitive-motor interventions affecting physical functioning: A systematic review. *BMC Geriatriccs BMC series*.

de Dieuleveult, A. L., Siemonsma, P. C., van Erp, J. B., & Brouwer, A. M. (2017). Effects of aging in multisensory integration: a systematic review. *Frontiers in aging neuroscience*, *9*, 80.

Delorme A & Makeig S (2004) EEGLAB: an open-source toolbox for analysis of single-trial EEG dynamics, Journal of Neuroscience Methods 134:9-21.

Delorme, A., Sejnowski, T., & Makeig, S. (2007). Enhanced detection of artifacts in EEG data using higher-order statistics and independent component analysis. *Neuroimage*, *34*(4), 1443-1449.

Dewhurst, S., & Bampouras, T. M. (2014). Intraday reliability and sensitivity of four functional ability tests in older women. *American journal of physical medicine & rehabilitation*, *93*(8), 703-707.

Diederich, A., & Colonius, H. (2004). Bimodal and trimodal multisensory enhancement: effects of stimulus onset and intensity on reaction time. *Perception & psychophysics*, *66*(8), 1388-1404.

Donohue, S. E., Green, J. J., & Woldorff, M. G. (2015). The effects of attention on the temporal integration of multisensory stimuli. *Frontiers in Integrative Neuroscience*, *9*, 32.

Fox J, Weisberg S (2019). An R Companion to Applied Regression, Third edition. Sage, Thousand Oaks CA. https://socialsciences.mcmaster.ca/jfox/Books/Companion/.

Foxe, J.J., Simpson, G.V. & Ahlfors, S.P. (1998) Parieto-occipital approximately 10 Hz activity reflects anticipatory state of visual attention mechanisms. *Neuroreport, 9*, 3929–3933.

Franzen, L., Delis, I., De Sousa, G., Kayser, C., & Philiastides, M. G. (2020). Auditory information enhances post-sensory visual evidence during rapid multisensory decision-making. *Nature communications*, *11*(1), 5440.

Gatehouse, S., & Noble, W. (2004). The speech, spatial and qualities of hearing scale (SSQ). *International journal of audiology*, *43*(2), 85-99.

Gazzaley, A., Cooney, J. W., Rissman, J., & D'esposito, M. (2005). Top-down suppression deficit underlies working memory impairment in normal aging. *Nature neuroscience*, *8*(10), 1298-1300.

Getzmann, S., Klatt, L. I., Schneider, D., Begau, A., & Wascher, E. (2020). EEG correlates of spatial shifts of attention in a dynamic multi-talker speech perception scenario in younger and older adults. *Hearing Research*, *398*, 108077.

Guralnik, J. M., Ferrucci, L., Pieper, C. F., Leveille, S. G., Markides, K. S., Ostir, G. V., ... & Wallace, R. B. (2000). Lower extremity function and subsequent disability: consistency across studies, predictive models, and value of gait speed alone compared with the short physical performance battery. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *55*(4), M221-M231.

Guralnik, J. M., Simonsick, E. M., Ferrucci, L., Glynn, R. J., Berkman, L. F., Blazer, D. G., ... & Wallace, R. B. (1994). A short physical performance battery assessing lower extremity function: association with self-reported disability and prediction of mortality and nursing home admission. *Journal of gerontology*, *49*(2), M85-M94.

H. Wickham. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York, 2016.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. *Psychology of learning and motivation*, *22*, 193-225.

Jansen, A. P., van Hout, H. P., Nijpels, G., van Marwijk, H. W., Gundy, C., de Vet, H. C., & Stalman, W. A. (2008). Self-reports on the IQCODE in older adults: a psychometric evaluation. *Journal of geriatric psychiatry and neurology*, *21*(2), 83-92.

Jones, S. A., & Noppeney, U. (2021). Ageing and multisensory integration: A review of the evidence, and a computational perspective. *Cortex*, *138*, 1-23.

Jorm, A. F. (2004). The Informant Questionnaire on cognitive decline in the elderly (IQCODE): a review. *International psychogeriatrics*, *16*(3), 275.

Kabacoff, R. I. (2015). *R in action: data analysis and graphics with R*. Simon and Schuster. P. 250

Kahya, M., Moon, S., Ranchet, M., Vukas, R. R., Lyons, K. E., Pahwa, R., ... & Devos, H. (2019). Brain activity during dual task gait and balance in aging and age-related neurodegenerative conditions: a systematic review. *Experimental gerontology*, *128*, 110756.

Keil, J., & Senkowski, D. Neural Oscillations Orchestrate Multisensory Processing. Neurosci. 2018, 24, 609–626

Keller, A.S., Payne, L., & Sekuler, R. Characterizing the roles of alpha and theta oscillations in multisensory attention. Neuropsychologia 2017, 99, 48–63.

Kelly, S.P.; Lalor, E.C.; Reilly, R.B.; Foxe, J.J. Increases in Alpha Oscillatory Power Reflect an Active Retinotopic Mechanism for Distracter Suppression During Sustained Visuospatial Attention. J. Neurophysiol. 2006, 95, 3844–3851.

Klatt, L. I., Schneider, D., Schubert, A. L., Hanenberg, C., Lewald, J., Wascher, E., & Getzmann, S. (2020). Unraveling the relation between EEG correlates of attentional orienting and sound localization performance: a diffusion model approach. *Journal of Cognitive Neuroscience*, *32*(5), 945-962.

Klimesch, W. (2012). Alpha-band oscillations, attention, and controlled access to stored information. *Trends in cognitive sciences*, *16*(12), 606-617.

Krebber, M., Harwood, J., Spitzer, B., Keil, J., & Senkowski, D. (2015). Visuotactile motion congruence enhances gamma-band activity in visual and somatosensory cortices. *Neuroimage*, *117*, 160-169.

Lange, J., Keil, J., Schnitzler, A., van Dijk, H., & Weisz, N. (2014). The role of alpha oscillations for illusory perception. *Behavioural brain research*, *271*, 294-301.

Laurienti, P. J., Burdette, J. H., Maldjian, J. A., & Wallace, M. T. (2006). Enhanced multisensory integration in older adults. *Neurobiology of aging*, *27*(8), 1155-1163.

Lenth R (2023). emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.8.8, https://CRAN.R-project.org/package=emmeans.

Lim, S. K., & Kong, S. (2022). Prevalence, physical characteristics, and fall risk in older adults with and without possible sarcopenia. *Aging clinical and experimental research*, *34*(6), 1365-1371.

Lipardo, D. S., & Tsang, W. W. (2020). Effects of combined physical and cognitive training on fall prevention and risk reduction in older persons with mild cognitive impairment: a randomized controlled study. *Clinical rehabilitation*, *34*(6), 773-782.

Lüdecke et al., (2021). performance: An R Package for Assessment, Comparison and Testing of Statistical Models. Journal of Open Source Software, 6(60), 3139. https://doi.org/10.21105/joss.03139

Lüdecke, D., Ben-Shachar, M. S., Patil, I., Waggoner, P., & Makowski, D. (2021). performance: An R package for assessment, comparison and testing of statistical models. *Journal of Open Source Software*, *6*(60).

Mahoney, J. R., Holtzer, R., & Verghese, J. (2014). Visual-somatosensory integration and balance: evidence for psychophysical integrative differences in aging. *Multisensory research*, *27*(1), 17-42.

Mahoney, J. R., Li, P. C. C., Oh-Park, M., Verghese, J., & Holtzer, R. (2011). Multisensory integration across the senses in young and old adults. *Brain research*, *1426*, 43-53.

Malcolm, B. R., Foxe, J. J., Joshi, S., Verghese, J., Mahoney, J. R., Molholm, S., & De Sanctis, P. (2021). Aging-related changes in cortical mechanisms supporting postural control during base of support and optic flow manipulations. *European Journal of Neuroscience*, *54*(12), 8139-8157.

Montero-Odasso, M. M., Sarquis-Adamson, Y., Speechley, M., Borrie, M. J., Hachinski, V. C., Wells, J., ... & Muir-Hunter, S. (2017). Association of dual-task gait with incident dementia in mild cognitive impairment: results from the gait and brain study. *JAMA neurology*, *74*(7), 857-865.

Mozolic, J. L., Hugenschmidt, C. E., Peiffer, A. M., & Laurienti, P. J. (2008). Modality-specific selective attention attenuates multisensory integration. *Experimental brain research*, *184*(1), 39-52.

O'Sullivan, A.E.; Lim, C.Y.; Lalor, E. Look at me when I'm talking to you: Selective attention at a multisensory cocktail party can be decoded using stimulus reconstruction and alpha power modulations. Eur. J. Neurosci. 2019, 50, 3282–3295

Office for Health Improvement and Disparities. (2022, February). *Falls: Applying All Our Health.* Gov.uk. Available online: https://www.gov.uk/government/publications/falls-applying-all-our-health/falls-applying-all-our-health (accessed on 2 March 2022)

Oosterhuis, E. J., Slade, K., May, P. J. C., & Nuttall, H. E. (2023). Toward an understanding of healthy cognitive aging: the importance of lifestyle in cognitive reserve and the scaffolding theory of aging and cognition. *The Journals of Gerontology: Series B*, *78*(5), 777-788.

Ozdemir, R. A., Contreras-Vidal, J. L., & Paloski, W. H. (2018). Cortical control of upright stance in elderly. *Mechanisms of ageing and development*, *169*, 19-31.

Park, D. C., & Reuter-Lorenz, P. (2009). The adaptive brain: aging and neurocognitive scaffolding. *Annual review of psychology*, *60*(1), 173-196.

Peiffer, A. M., Mozolic, J. L., Hugenschmidt, C. E., & Laurienti, P. J. (2007). Age-related multisensory enhancement in a simple audiovisual detection task. *Neuroreport*, *18*(10), 1077-1081.

Pepper, J. L., & Nuttall, H. E. (2023a). Age-Related Changes to Multisensory Integration and Audiovisual Speech Perception. *Brain Sciences*, *13*(8), 1126.

Pepper, J. L., Usherwood, B., Bampouras, T. M., & Nuttall, H. E. (2023b). Age-related changes to the attentional modulation of temporal binding. *Attention, Perception, & Psychophysics*, 1-15.

Peterka, R. J. (1995). Simple model of sensory interaction in human postural control. In *Multisensory control of posture* (pp. 281-288). Boston, MA: Springer US.

Peterka, R. J. (2002). Sensorimotor integration in human postural control. *Journal of neurophysiology*, *88*(3), 1097-1118.

Pfurtscheller, G., Stancak Jr, A., & Neuper, C. (1996). Event-related synchronization (ERS) in the alpha band—an electrophysiological correlate of cortical idling: a review. *International journal of psychophysiology*, *24*(1-2), 39-46.

Pichierri, G., Murer, K., & de Bruin, E. D. (2012). A cognitive-motor intervention using a dance video game to enhance foot placement accuracy and gait under dual task conditions in older adults: a randomized controlled trial. *BMC geriatrics*, *12*(1), 1-14.

Podsiadlo, D., & Richardson, S. (1991). The timed “up & go”: A test of basic functional mobility for frail elderly persons. Journal of the American Geriatrics Society, 39, 142-148.

Poliakoff, E., Ashworth, S., Lowe, C., & Spence, C. (2006). Vision and touch in ageing: crossmodal selective attention and visuotactile spatial interactions. *Neuropsychologia*, *44*(4), 507-517.

Posner, M. I., & Driver, J. (1992). The neurobiology of selective attention. *Current opinion in neurobiology*, *2*(2), 165-169.

Powell, L. E., & Myers, A. M. (1995). The activities-specific balance confidence (ABC) scale. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *50*(1), M28-M34.

R Core Team (2022). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Raffi, M., & Piras, A. (2019). Investigating the crucial role of optic flow in postural control: Central vs. peripheral visual field. *Applied sciences*, *9*(5), 934.

Ramkhalawansingh, R., Keshavarz, B., Haycock, B., Shahab, S., & Campos, J. L. (2016). Age differences in visual-auditory self-motion perception during a simulated driving task. *Frontiers in psychology*, *7*, 595.

Reed-Jones, R. J., Solis, G. R., Lawson, K. A., Loya, A. M., Cude-Islas, D., & Berger, C. S. (2013). Vision and falls: a multidisciplinary review of the contributions of visual impairment to falls among older adults. *Maturitas*, *75*(1), 22-28.

Reuter-Lorenz, P. A., & Park, D. C. (2014). How does it STAC up? Revisiting the scaffolding theory of aging and cognition. *Neuropsychology review*, *24*, 355-370.

Rockwood, K., Rockwood, M. R., Andrew, M. K., & Mitnitski, A. (2008). Reliability of the hierarchical assessment of balance and mobility in frail older adults. *Journal of the American Geriatrics Society*, *56*(7), 1213-1217.

Sauseng, P., Klimesch, W., Stadler, W., Schabus, M., Doppelmayr, M., Hanslmayr, S., ... & Birbaumer, N. (2005). A shift of visual spatial attention is selectively associated with human EEG alpha activity. *European journal of neuroscience*, *22*(11), 2917-2926.

Scurry, A. N., Lovelady, Z., Lemus, D. M., & Jiang, F. (2021). Impoverished inhibitory control exacerbates multisensory impairments in older fallers. *Frontiers in aging neuroscience*, *13*, 700787.

Segev-Jacubovski, O., Herman, T., Yogev-Seligmann, G., Mirelman, A., Giladi, N., & Hausdorff, J. M. (2011). The interplay between gait, falls and cognition: can cognitive therapy reduce fall risk?. *Expert review of neurotherapeutics*, *11*(7), 1057-1075.

Setti, A., Burke, K. E., Kenny, R. A., & Newell, F. N. (2011). Is inefficient multisensory processing associated with falls in older people?. *Experimental brain research*, *209*(3), 375-384.

Sherrington, C., Whitney, J. C., Lord, S. R., Herbert, R. D., Cumming, R. G., & Close, J. C. (2008). Effective exercise for the prevention of falls: a systematic review and meta-analysis. *Journal of the American Geriatrics Society*, *56*(12), 2234-2243.

Shumway-Cook, A., Brauer, S., & Woollacott, M. (2000). Predicting the probability for falls in community-dwelling older adults using the timed up & go test. Physical Therapy, 80(9), 896-903.

Slade, K., Davies, R., Pennington, C. R., Plack, C. J., & Nuttall, H. E. (2023). The impact of age and psychosocial factors on cognitive and auditory outcomes during the COVID-19 pandemic. *Journal of Speech, Language, and Hearing Research*, *66*(9), 3689-3695.

Slobounov, S., Cao, C., Jaiswal, N., & Newell, K. M. (2009). Neural basis of postural instability identified by VTC and EEG. *Experimental brain research*, *199*, 1-16.

Stapleton, J., Setti, A., Doheny, E. P., Kenny, R. A., & Newell, F. N. (2014). A standing posture is associated with increased susceptibility to the sound-induced flash illusion in fall-prone older adults. *Experimental brain research*, *232*, 423-434.

Stein, B. E., & Wallace, M. T. (1996). Comparisons of cross-modality integration in midbrain and cortex. *Progress in brain research*, *112*, 289-299.

Stern, Y., Arenaza-Urquijo, E. M., Bartrés-Faz, D., Belleville, S., Cantilon, M., Chetelat, G., ... & Reserve, Resilience and Protective Factors PIA Empirical Definitions and Conceptual Frameworks Workgroup. (2020). Whitepaper: Defining and investigating cognitive reserve, brain reserve, and brain maintenance. *Alzheimer's & Dementia*, *16*(9), 1305-1311.

Stevenson, R. A., Fister, J. K., Barnett, Z. P., Nidiffer, A. R., & Wallace, M. T. (2012a). Interactions between the spatial and temporal stimulus factors that influence multisensory integration in human performance. *Experimental Brain Research*, *219*(1), 121-137.

Talsma, D., Doty, T. J., & Woldorff, M. G. (2007). Selective attention and audiovisual integration: is attending to both modalities a prerequisite for early integration?. *Cerebral cortex*, *17*(3), 679-690.

Talsma, D.; Senkowski, D.; Soto-Faraco, S.; Woldorff, M.G. The multifaceted interplay between attention and multisensory integration. Trends Cogn. Sci. 2010, 14, 400–410.

Thomas, N. M., Bampouras, T. M., Donovan, T., & Dewhurst, S. (2016). Eye movements affect postural control in young and older females. *Frontiers in aging neuroscience*, *8*, 216.

Thut, G., Nietzel, A., Brandt, S. A., & Pascual-Leone, A. (2006). α-Band electroencephalographic activity over occipital cortex indexes visuospatial attention bias and predicts visual target detection. *Journal of Neuroscience*, *26*(37), 9494-9502.

Topolski, T. D., LoGerfo, J., Patrick, D. L., Williams, B., Walwick, J., & Patrick, M. M. B. (2006). Peer reviewed: the Rapid Assessment of Physical Activity (RAPA) among older adults. *Preventing chronic disease*, *3*(4).

Turunen, K. M., Tirkkonen, A., Savikangas, T., Hänninen, T., Alen, M., Fielding, R. A., ... & Sipilä, S. (2022). Effects of physical and cognitive training on falls and concern about falling in older adults: results from a randomized controlled trial. *The Journals of Gerontology: Series A*, *77*(7), 1430-1437.

Uemura, K., Yamada, M., Nagai, K., Tanaka, B., Mori, S., & Ichihashi, N. (2012). Fear of falling is associated with prolonged anticipatory postural adjustment during gait initiation under dual-task conditions in older adults. *Gait & posture*, *35*(2), 282-286.

van Driel, J., Gunseli, E., Meeter, M., & Olivers, C. N. (2017). Local and interregional alpha EEG dynamics dissociate between memory for search and memory for recognition. *Neuroimage*, *149*, 114-128.

van Het Reve, E., & de Bruin, E. D. (2014). Strength-balance supplemented with computerized cognitive training to improve dual task gait and divided attention in older adults: a multicenter randomized-controlled trial. *BMC geriatrics*, *14*(1), 1-15.

Wöstmann, M., Lim, S. J., & Obleser, J. (2017). The human neural alpha response to speech is a proxy of attentional control. *Cerebral cortex*, *27*(6), 3307-3317.

Yelnik, A., & Bonan, I. (2008). Clinical tools for assessing balance disorders. *Neurophysiologie Clinique/Clinical Neurophysiology*, *38*(6), 439-445.

Zhang, S.; Xu, W.; Zhu, Y.; Tian, E.; Kong, W. Impaired Multisensory Integration Predisposes the Elderly People to Fall: A Systematic Review. Front. Neurosci. 2020, 14, 411.

Zhuravleva, T. Y., Alperin, B. R., Haring, A. E., Rentz, D. M., Holcomb, P. J., & Daffner, K. R. (2014). Age-related decline in bottom-up processing and selective attention in the very old. *Journal of clinical neurophysiology: official publication of the American Electroencephalographic Society*, *31*(3), 261.

5. The Role of Age-Related Changes in Alpha Activity During Dual-Task Speech Perception and Balance

5.1. Linking Statement

The previous two chapters have involved investigating the mechanisms of audiovisual integration using relatively simple sensory stimuli. Whilst this has provided important insights with regards to how bottom-up and top-down elements of multisensory integration may change with healthy ageing (Setti et al., 2011; Hirst et al., 2019), it is also crucial to consider how such mechanisms may manifest during complex tasks like speech perception. In our noisy, dynamic everyday lives, it is very rare that we are performing one multisensory task in isolation. Instead, speech perception is often accompanied by simultaneous motor demands associated with balance maintenance, such as walking, cooking and shopping (Helfer et al., 2020). With increasing age, these dual-task abilities may deteriorate, due to the increased difficulty that older adults may experience with flexibly allocating attentional resources to two co-occurring multisensory tasks. These difficulties are exacerbated when cognitive load is high (Lajoie et al., 1993; Helfer et al., 2020), such as perceiving speech in adverse listening environments or maintaining challenging balance. Once again, oscillatory alpha power may cast light on how the reallocation of attentional resources changes as a function of healthy ageing, and the impact that such changes have on an older adult's speech perception and fall risk.

This study investigated age-related changes in oscillatory alpha activity during simultaneous balance maintenance and speech perception. Using a dual-task paradigm, younger and older participants identified key words within sentences (retrieved from the Grid corpus; Cooke et al., 2006) in clear or noisy listening environments, whilst standing in easy or difficult balance positions. The proportion of words correctly identified by younger and older adults in each condition was compared. Neural data was measured using EEG throughout the task, to identify differences in parieto-occipital and fronto-central alpha power when younger and older adults allocated attentional resources between speech perception and balance maintenance. The findings of these preliminary data indicate that older adults may be more robust to age-related changes in attentional control than once thought, and may effectively employ compensatory strategies to preserve speech perception and balance performance. Potential reasons for this are discussed within the chapter, with a particular emphasis on the importance of "cognitive reserve" theories (Stern et al., 2020) in understanding heterogenous ageing trajectories, and the impact of this on perceptual and cognitive performance.

Author note: *The study hypotheses, design and statistical analyses were pre-registered online on the Open Science Framework:* https://doi.org/10.17605/OSF.IO/JD7NE. *This manuscript was prepared in collaboration with Dr Theodoros Bampouras and Dr Helen Nuttall.*

5.2. Abstract

Research suggests that older adults find it more difficult than younger adults to flexibly allocate attentional resources between two co-occurring multisensory tasks, such as perceiving speech whilst maintaining balance. This attentional control may be reflected in oscillatory alpha activity, with increases in activity reflecting inhibition of different brain regions and decreases reflecting neural activation. However, there is limited research examining how alpha activity during dual-task conditions may change as a function of healthy ageing. This study aimed to investigate how younger and older adults reallocate attentional resources during dual-task conditions, and how these age-related changes are reflected in alpha activity; it is important to develop a comprehensive understanding of the impact of such changes on everyday speech perception and balance maintenance in our increasingly ageing population.

Nineteen younger adults (18-35 years old) and sixteen older adults (60-80 years old) were asked to identify words in audiovisual sentences extracted from the Grid corpus. Participants completed this speech perception task in either a clear listening environment or a noisy listening environment, whilst standing in an easy balance position (feet side-by-side) or a hard balance position (feet in tandem). Throughout the task, fronto-central and parieto-occipital alpha activity was recorded using EEG, to measure activation in brain regions associated with balance maintenance and audiovisual speech perception, respectively.

Mixed ANCOVAs revealed that all participants produced a weaker speech perception performance in noisy listening conditions. However, speech perception performance in the noisy listening condition was strongest when participants stood in a challenging balance position, in contrast to our hypotheses. Whilst these behavioural effects were not reflected by fluctuations in parieto-occipital alpha power, decreases in fronto-central alpha power were greater in clear listening conditions compared to noisy listening conditions. Taken together, the results suggest that increasing cognitive load with a secondary multisensory task may not always be detrimental to balance maintenance in physically and cognitively fit older adults.

Word count: 311
Key words: attention, dual-task, multisensory, alpha, speech, balance, ageing

5.3. Introduction

Quick and accurate audiovisual speech perception in a multitalker environment requires the focussing of attention on congruent visual and auditory inputs from one speaker, and the suppression of distracting, irrelevant background speech (Begau et al., 2022; Dey & Sommers, 2015). With increasing age, speech perception becomes more challenging, particularly in noisy listening environments (Tremblay et al., 2021; Helfer et al., 2017, Roberts & Allen, 2016; Getzmann et al., 2016). Indeed, whilst difficulties in speech perception are exacerbated by age-related hearing loss (Slade et al., 2020), a fundamental top-down contributor is that the ability to inhibit distracting background information has been found to weaken with healthy ageing (Borghini et al., 2018; Gazzaley et al., 2005; Gazzaley et al., 2008; Fabiani et al., 2006; Hasher et al., 2007). Crucially, age-related deficits in attentional control result in less accurate audiovisual integration, increased cognitive load and greater difficulty perceiving speech in adverse listening conditions.

In laboratory testing, audiovisual speech perception is often investigated by asking participants to listen and respond to speech in the form of an isolated, seated computer task. However, in everyday life settings, speech perception is much more complex and dynamic, often involving multitasking, with demands placed on the motor system. For example, people regularly communicate whilst simultaneously completing other activities of daily living, such as walking, shopping or cooking (Helfer et al., 2020). As such, it is important to research whether age-related changes in attentional control can impact the ability to successfully carry out combined cognitive-motor tasks (Helfer et al., 2020); specifically, whether speech perception is made increasingly challenging due to the simultaneous attentional demands associated with balance maintenance. Indeed, whilst an older adult's vision and hearing loss

(Reed-Jones et al., 2013; Campos et al., 2018), muscle loss (Lim & Kong, 2022), and prescription to certain medications (Callis et al., 2016) may have an adverse effect on their balance ability, research also suggests that weaker attentional control can also negatively affect balance and predict fall risk (Hegeman et al., 2012; Montero-Odasso et al., 2012). Taken together, both weaker speech perception and unstable balance can have a significant impact on older adults' quality of life, with many feeling reluctant to visit busy places and withdrawing from social situations (Slade et al., 2020; Weissgerber et al., 2022).

However, at this point, it is important to note that ageing trajectories are heterogenous, with some older adults being more robust to the negative effects of ageing compared to others (Daskalopoulou et al., 2019; Oosterhuis et al., 2023). For example, external factors such as years of education, amount of socialisation, and levels of physical activity can contribute to "cognitive reserve" (Stern et al., 2020; Oosterhuis et al., 2023). Older adults with higher levels of cognitive reserve can strengthen existing brain networks to facilitate the use of alternative cognitive strategies (Stern et al., 2020; Oosterhuis et al., 2023); this cognitive flexibility can potentially preserve performance in tasks that would have otherwise been challenged by the ageing process, like speech perception and balance maintenance. In contrast, older adults with lower cognitive reserve, or those who experience wider issues like health inequalities and cognitive frailty (Tan et al., 2022; Franse et al., 2017), are more likely to exhibit the negative effects of ageing discussed previously, such as weaker speech perception and increased fall risk. Despite these individual differences, and given our increasingly ageing population, it is important to investigate the attentional mechanisms involved in simultaneously understanding speech and maintaining balance, and how this may change as a function of healthy ageing.

The joint impact of age-related changes in speech perception and balance maintenance is often investigated using dual-task methodologies, manipulating the cognitive load required to maintain balance and assessing the impact that this has on performance in a secondary multisensory speech perception task (Lajoie et al., 1993). Humans possess a limited amount of attentional resources which must be divided efficiently for accurate performance in any cognitive or motor tasks (Wingfield et al., 2016; Slade et al., 2020). When one task is more difficult and increases cognitive load, this may exceed the attentional capacities of older adults, resulting in decreased performance in one or both tasks (Ruffieux et al., 2015; Helfer et al., 2020). Data indicate that older adults prioritise balance maintenance over any co-occurring cognitive or motor tasks, adopting a "posture first" strategy to prevent falling (Brauer et al., 2002; Ozdemir et al., 2016). In a dual-task situation, if balance is more challenging for older adults due to neuromuscular or unisensory declines, they may allocate increased attentional resources to maintaining balance (Hulsdunker et al., 2016; Woollacott & Shumway-Cook, 2002), to the detriment of their performance in a secondary multisensory task such as speech perception (Pepper & Nuttall, 2023; Boisgontier et al., 2013). Likewise, if older adults are asked to perceive speech amongst distracting background noise, the resulting high cognitive load may divert attentional resources away from balance and lead to increased fall risk (Pepper & Nuttall, 2023; Setti et al., 2011; Wajda et al., 2017; Ruffieux et al., 2015).

Many studies have previously found that, in older adults, postural control shifts from supra-spinal neural pathways to higher cortical networks (Ozdemir et al., 2016). Specifically, due to age-related impairments in supra-spinal sensorimotor tracts responsible for automatic posture, older adults may rely on higher-level cortical processing loops as a compensatory strategy to maintain balance (Ozdemir et al., 2016; Boisgontier & Nougier, 2013). In this way, allocating an increased amount of cognitive resources to postural control can have a negative impact on any concurrent cognitive tasks due to limited attentional capacity (Kahya et al., 2019; Ozdemir et al., 2016; Boisgontier & Nougier, 2013; Goble et al., 2010). This is supported by research by Ozdemir et al. (2016), who found that older adults who had a high cognitive capacity (i.e. a higher response accuracy in a working memory task) displayed less postural sway during challenging balance conditions, indicating the important role that availability of cognitive resources has on balance maintenance in older adults. Likewise, older adults with cognitive impairment, who may not have the availability or flexibility required to efficiently allocate attentional resources, are at an increased risk of falls even when their motor control is preserved (Eriksson et al., 2008; van Iersel et al., 2006).

Oscillations in the alpha-band frequency (8-12Hz) are believed to be neural correlates of attentional and inhibitory mechanisms (Lange et al., 2014; Pepper et al., 2023; Kelly et al., 2006). Increases in alpha activity in parieto-occipital regions reflect the suppression of noisy, irrelevant sensory information during audiovisual processing (Lange et al., 2014; Keller et al., 2017; Keil & Senkowski, 2017), whereas decreases in alpha activity in these regions indicate increased activation, facilitating the processing of congruent sensory inputs which should be integrated (Kelly et al., 2006; Thut et al., 2006; Rihs et al., 2007). For example, O'Sullivan et al., (2016) found that when participants were presented with incongruent visual and auditory speech information, parieto-occipital alpha power increased, inhibiting the visual inputs to prevent erroneous integration. However, when visual and auditory inputs were congruent, alpha activity decreased – this facilitated integration of the visual and auditory information to produce a quick and accurate percept of the speech. In addition, with regards to speech perception in adverse listening conditions, Wostmann et al. (2017) found that parietal alpha power increased when highly distracting background speech had to be inhibited. It follows that if older adults experience increased difficulty in inhibiting background speech in noisy listening environments, this may be reflected in lower increases in parieto-occipital alpha power compared to younger adults. In this way, increases and decreases in alpha power can be used to identify the extent to which younger and older adults are able to inhibit distracting sensory inputs and divert attentional resources towards audiovisual integration for speech perception.

Alpha oscillations have also been used to investigate the cortical brain regions involved in balance. During challenging balance conditions, previous research has found that alpha power decreases in central brain regions (Kahya et al., 2022; Hulsdunker et al., 2015; Del Percio et al., 2009; Slobounov et al., 2009; Beurskens et al., 2016) compared to easier balance conditions. These decreases in alpha power have been interpreted as increased information processing during postural instability (Edwards et al., 2018; Hulsdunker et al., 2015). That is, whilst increases in parieto-occipital alpha power may reflect the inhibition of task-irrelevant audiovisual information, decreases in fronto-central alpha power in may reflect increased recruitment of relevant cognitive-motor resources to maintain balance (Kahya et al., 2022; Hulsdunker et al., 2016; Beurskens et al., 2016; Shaw et al., 2018). Indeed, older adults are believed to show increased global neural activity during dual-task conditions than single tasks, compared to younger adults (Kahya et al., 2019; Ozdemir et al., 2016; Rosso et al., 2017). If older adults are more reliant on cortical brain regions to maintain balance due to neurodegeneration of subcortical balance centres, this could be reflected in greater decreases in fronto-central alpha activity as a compensatory strategy to reduce incidence of falls.

This study investigated whether age-related changes in oscillatory alpha power reflects the allocation of attentional resources in younger and older adults during dual-task speech perception and balance maintenance. Younger and older adults completed an audiovisual speech perception task in which they were asked to identify key words from the Grid corpus (Cooke et al., 2006), in clear or noisy listening environments. Simultaneously, participants were asked to maintain their balance, in an easy balance position (feet side-by-side) or a hard balance position (feet in tandem), whilst their sway velocity was recorded. Alpha activity in fronto-central and parieto-occipital brain regions was recorded throughout using EEG. The hypotheses were as follows:

1. Older adults' speech perception will be more negatively affected by difficult balance conditions than by easy balance conditions, relative to younger adults.
2. Older adults' speech perception in noisy conditions will be more negatively affected by difficult balance than in clear conditions, relative to younger adults.
3. Participants will display decreased fronto-central alpha power in difficult balance conditions compared to easy balance conditions.
4. Older adults will produce larger decreases in fronto-central alpha power than younger adults in difficult balance conditions.
5. Participants will show increased parieto-occipital alpha power in noisy listening environments compared to clear listening environments.
6. Older adults will display smaller increases in parieto-occipital alpha power during noisy listening conditions than younger adults.

5.4. Methods

5.4.1. Participants

Data analysed will be based on 19 younger adults (8 males, 11 females) between 18-35 years old (*M* = 22.47, *SD* = 4.43) and 16 older adults (6 males, 10 females) between 60-80 (*M* = 69.63, *SD* = 5.28). The full sample size required for this study to be adequately powered was determined via an a-priori power analysis using the ANOVA_power Shiny application (Lakens & Caldwell, 2019; see pre-registration on Open Science Framework: https://doi.org/10.17605/OSF.IO/JD7NE). This required collecting the means and standard deviations reported in Helfer et al. (2020), who conducted a similar study examining age-related changes in postural control during a speech perception task. The minimum sample size was systematically altered to achieve a simulated power of 80% or higher for as many of the main effects and interactions as feasibly possible. Using a power of 80% and an alpha value of 0.017 to correct for multiple comparisons, the ANOVA_power app indicated that a minimum sample size of 60 per group was required.

Participants were eligible for the study if they were fluent English speakers with normal or corrected-to-normal vision, screened for via self-report. Participants were ineligible to proceed with the experiment if they had a history or current diagnosis of cognitive impairments or neurological conditions (e.g. epilepsy, mild cognitive impairment, dementia, Parkinson’s Disease) or learning impairments (e.g. dyslexia). Participants were also ineligible to participate if they suffered from motion sickness; if they were diagnosed with any vestibular impairments (e.g. vertigo) or numbness in the lower limbs; if they were diagnosed with any muscle or bone conditions which could prevent standing comfortably (including lower limb, hip or spine surgery within the last year, or recent injury); if they relied on assistive walking devices (e.g. canes or walking frames), or if they were on medication which depresses the nervous system or affects balance (Thomas et al., 2016).

Participants were recruited via opportunity sampling; younger participants were students at Lancaster University, whilst older participants were recruited through the Centre for Ageing Research at Lancaster University, or through advertising to local community groups, such as University of the Third Age. All participants provided informed consent. Ethical approval was received from Lancaster University Faculty of Science and Technology Ethics Committee (ref: FST-2023-3499-RECR-3).

5.4.2. Pre-screening tools

Informant Questionnaire on Cognitive Decline in the Elderly (IQ-CODE; Appendix B; Jorm, 2004).

Older adult participants used a self-report version of the IQ-CODE to rate how their performance in certain tasks now has changed compared to 10 years ago, answering on a 5-point Likert scale (1="Much Improved", 5="Much worse"). An average score of approximately 3.65 is the usual cut-off point when evaluating cognitive impairment and dementia (Jansen et al., 2008; Slade et al., 2024), therefore people whose average score was higher than 3.65 were not eligible to participate in the experiment. This was to ensure that any age-related changes in audiovisual integration measured in the task would not be due to the participant experiencing mild cognitive impairment. The mean IQ-CODE score of the older adult participants in this study was 3.04 (*SD* = 0.21).

Pure-Tone Audiometry Assessment (British Society of Audiology, 2018)

To confirm that younger participants had normal hearing and older participants' age-related hearing loss did not exceed moderate, participants completed a pure-tone audiometry assessment, following the guidelines established by the British Society of Audiology (2018). Pure-tone thresholds were measured at 0.25 kHz, 0.5 kHz, 1 kHz, 2 kHz, 4 kHz and 8 kHz bilaterally, with thresholds averaged from the 0.5 kHz, 1kHz, 2kHz and 4kHz frequencies to determine the pure-tone average across both ears. Normal hearing is defined as pure tone thresholds ≤20dB at 0.5-4 kHz. We expected older adults to have higher thresholds due to age-related hearing loss, as such they were required to have pure tone thresholds ≤40dB at 0.5-4kHz (Li et al., 2020). This was to ensure that any age-related differences in multisensory performance was not due to moderate or severe hearing loss in the older adult sample.

An independent *t*-test revealed that there was a significant difference in PTA thresholds between age groups [*t*(33) = -6.70, *p*<.001); a higher PTA threshold was recorded in older adults (*M* = 18.52, *SD* = 7.53) compared to younger adults (*M* = 4.54, *SD* = 4.70). PTA data for each age group, at each frequency, is displayed in *Figure 1.*

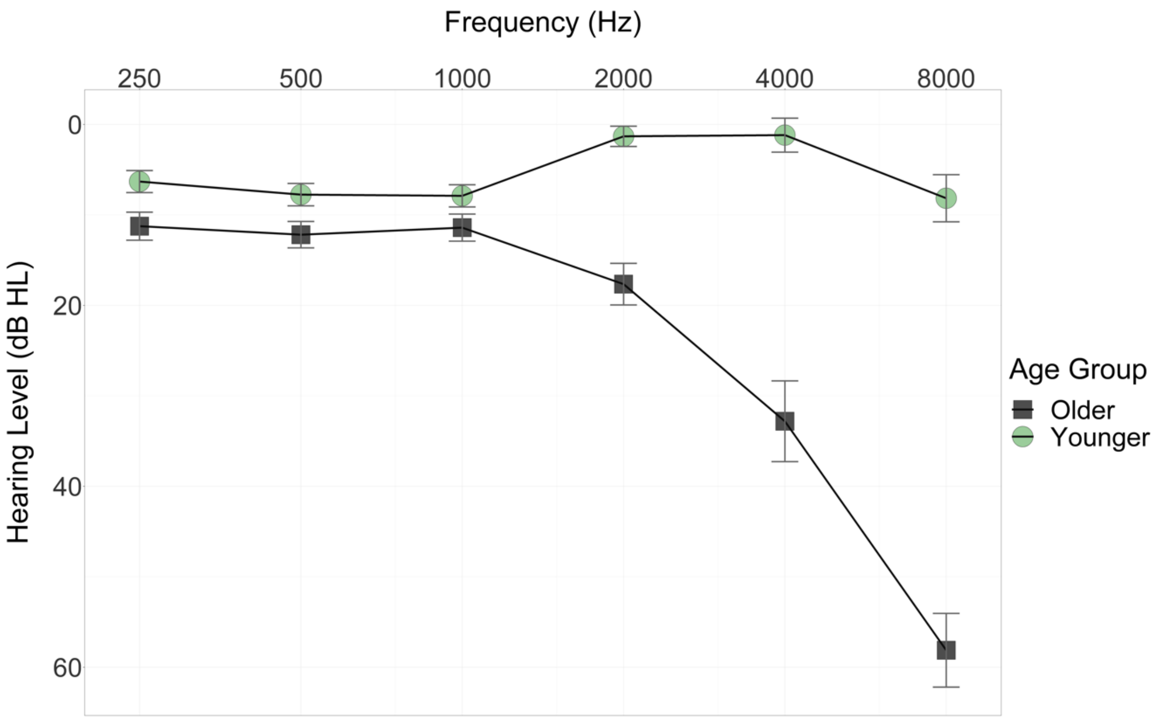


Figure 1. Pure-tone audiometry thresholds, in db HL, for each age group at each frequency. Younger adult means are represented in green, older adult means are represented in grey.

5.4.3. Experimental Design

Questionnaire Measures

Upon arrival at the lab, participants completed two self-report assessments of physical activity, providing detailed information regarding participants' own perception of their balance abilities and their fitness levels.

Activities-Based Balance Confidence Scale (ABC; Appendix C; Powell & Myers, 1995). The ABC scale is a 16-item questionnaire used to assess participants' balance confidence in performing daily activities. Participants were asked to rate how confident they are in performing each activity, on a 10-point scale ranging from 0% (not confident at all) to 100%

(completely confident). An average score of greater than 80% indicates high levels of functioning; a score of between 50% and 80% indicates moderate levels of functioning; a score of less than 50% indicate low levels of functioning. Crucially, a score of less than 67% is indicative of a substantial risk of falling.

Rapid Assessment of Physical Activity (RAPA; Appendix D; Topolski et al., 2006). The RAPA is a 9-item questionnaire used to assess the level of physical activity in the samples. Participants are presented with 9 scenarios relating to the amount and intensity of their physical activity, in which they are asked to answer Yes/No to whether the physical activity level in the scenario accurately describes them. The scale is divided into two parts. RAPA1 consists of 7 items and measures cardio-respiratory, aerobic activity. The highest affirmative score provided by participants is their final recorded score for RAPA1 (scored as 1 = "Sedentary", 2 = "underactive", 3 = "underactive regular - light activities", 4 and 5 = "underactive regular", 6 and 7 = "Active"). RAPA2 consists of 2 items and measures strength and flexibility-based physical activity. An affirmative response to the first item results in a score of 1; an affirmative response to the second item results in a score of 2; affirmative responses to both items scores 3; negative responses to both items scores 0. Participants' scores on RAPA1 and RAPA2 were added together to provide an overall indication of physical activity levels of the samples. Higher total scores represent higher levels of physical activity.

Speech perception task

This study implemented a 2 (Age: Younger vs Older) x 2 (Stance: Easy vs Hard) x 2 (Listening Condition: Clear vs Noisy) mixed design, with Age as the between-subjects factor, and Stance and Listening Condition as within-subjects factors. The experiment consisted of 4 different combinations of conditions:

1. Easy stance, clear listening condition (EasyClear)
2. Easy stance, noisy listening condition (EasyNoise)
3. Hard stance, clear listening condition (HardClear)
4. Hard stance, noisy listening condition (HardNoise)

Each participant completed two blocks of 24 trials for each condition (48 trials per condition in total). Participants were assigned to one of 4 groups, which determined the counterbalanced order in which each block was presented. After every 8 trials, participants had the opportunity for a break. Participants also completed 48 clear trials whilst seated and 48 noisy trials whilst seated – these were the single-task conditions, allowing for the calculation of dual-task costs in speech perception performance which may arise from adding the balance task. The duration of the task was approximately 1.5 hours in total.

Speech perception: materials. All sentences used in the task were extracted from the Grid corpus (Cooke et al., 2006). The Grid is a large audiovisual sentence corpus comprising of high-quality facial recordings of 1000 sentences spoken by each of 34 talkers. Speaker 29 of the Grid corpus was used for each trial of this experiment. The duration of each sentence was 3 seconds, and each sentence had the same structure – command, colour, preposition, letter, number, adverb, such as "lay green at C 4 please" *(Table 1).* Participants were asked to identify the letter and the number that was spoken in each trial.

Table 1

Structure of sentences within the GRID corpus. Each participant was asked to identify the letter and the number spoken in each sentence.

Command	Colour	Preposition	**Letter**	**Number**	Adverb
Place	Red	At	A-Z, excluding letter W	0-9	Now
Lay	White	By			Again
Bin	Blue	In			Soon
Set	Green	With			Please

Participants watched and listened to the sentences being spoken in clear listening environments (no noise), and in noisy listening environments, in which the target sentence was accompanied by 4-talker babble noise. This 4-talker babble noise was created using male and female voices taken from the Clarity Speech Corpus (Graetzer et al., 2022). The noise clips were the same duration, and had the same onset and offset, as the audiovisual Grid sentence. Four different noise audio clips were created; one of four clips were played in each trial of the noisy listening condition. Noise was added at a signal-to-noise ratio of -15dB, modulated using Audacity (version 3.3.3). Each stimulus presentation lasted for 3 seconds.

Speech perception: experimental paradigm. Participants first completed the seated clear and noisy practice blocks consisting of 10 trials each, before proceeding to the seated single-task clear and noisy blocks. After this, participants completed single-task side-by-side and tandem balance measurements, in which their sway velocity was recorded for 60 seconds each – participants were asked to focus on a fixation cross on the screen throughout these single-task balance measurements, with their hands by their sides. After this, the dual-task phase of the experiment began. Participants stood with their hands by their sides facing the computer, with feet in either a side-by-side (easy) or tandem (hard) position. A prompt was displayed on the screen at the beginning of each block to instruct participants which stance to adopt. At the start of each trial, participants were presented with a fixation cross lasting 1.5 seconds. After this, the audiovisual speech video was played, in either a clear or noisy listening environment. At the end of the video, participants were asked to press the corresponding keys on the keyboard to identify the letter and number spoken, returning their hand to their side before the start of the next video.

The experiment was completed in a soundproof booth on an Apple Mac computer (version 12.2.1) with a standard keyboard. All participants wore EEG-compatible earphones (ER2 ultra-shielded insert earphones; Intelligent Hearing Systems). A standing desk was used to ensure that the computer screen was at an appropriate height for all participants, at eye-level and ensuring that the keyboard was at a comfortable reaching distance.

Balance measures

Sway velocity was recorded during the easy and hard balance conditions using a smartphone with a built-in inertial measurement unit (IMU). The smartphone was positioned in a holster slightly below the participants' waistband to avoid excess instability and noise from breathing movements. The IMU sensor signals were sampled at 50Hz using the Lockhart Monitor iPhone app (Locomotion Research Laboratory, Arizona State University; iOS App Store). The Lockhart Monitor measures linear and nonlinear parameters of a person's postural stability, recording sway velocity, sway area and sway path (Doshi et al., 2023). The app consists of a start and stop button for recording. Each balance recording lasted 60 seconds, which is the maximum duration possible on the Lockhart Monitor app. Due to the fact that each block of 24 sentences lasted 3 minutes (8 trials per minute, then a break), this resulted in three balance recordings per block. The sway velocity from each of these balance recordings was averaged to provide one grand average sway velocity for each participant in each block.

5.4.4. EEG Data Acquisition and Pre-Processing

Continuous EEG data were sampled at 500Hz from a 32-channel EEG amplifier system (BrainAmps, BrainProducts GmbH, Germany) with Ag/AgCl electrodes positioned according to the international 10-20 system (actiCAP EasyCap, BrainProducts, GmbH, Germany), referenced to the central Reference electrode during recording. Psychopy and BrainVision Recorder (version 1.10, Brain Products GmbH, Germany) were used in conjunction to record trial-specific information in real time, including EEG triggers coded to identify the condition each participant experienced (Franzen et al., 2020; Klatt et al., 2020).

Processing and EEG analyses were completed offline using the EEGLAB toolbox (Delorme & Makeig, 2004) and MATLAB scripts. The EEG data were first resampled to 250Hz, re-referenced to the average of all electrodes, and a digital low cut-off filter of 0.1Hz and a high cut-off filter of 44Hz was applied. Breaks between experimental blocks were removed and an independent component analysis (ICA) was performed on the data. Artefactual independent components were detected and rejected using the ICFlag function in EEGLAB; components that were identified as being over 80% likely to be heart, muscle or eye artefacts were removed from the dataset (Delorme et al., 2007). The pre-processed EEG data were then epoched; the epoch started 1000ms before the video was presented, recording EEG data whilst the participant was looking at the fixation cross. The epoch ended 3000ms after the video was presented, recording EEG data whilst the participant watched and listened to the full duration of the audiovisual speech.

Alpha power extraction

Alpha power was extracted from the 8-12Hz frequency band at electrodes positioned over the parietal and occipital regions (P3, P4, P7, P8, O1, O2, Oz), as well as over frontal and central regions (F3, F4, Fz, FC5, FC1, FC2, FC6). Alpha power was determined using the power spectral density (PSD) package in EEGLAB. The 'spectopo' function is based upon Welsch's method and uses a 256-point Hamming window. Within each epoch, for each participant, mean alpha power over each electrode was calculated for the 1000ms pre-stimulus interval of each condition type (fixation cross), and for the 3000ms audiovisual condition type (video clip). The alpha power was then averaged across all electrodes of interest, to produce a grand mean alpha power value for the experimental condition, and a grand mean alpha power for the pre-stimulus baseline associated with each condition, for each electrode cluster. Mean baseline alpha power was then subtracted from mean experimental alpha power to produce an alpha power value representative of the difference in alpha power between ‘rest’ (pre-stimulus interval) and the experimental trial. This means that each participant had a mean alpha power difference value for fronto-central regions and a mean alpha power difference value for parieto-occipital regions, each of which were used as the main outcome variables in the EEG analyses.

5.4.5. Procedure

The procedure for this study is displayed in Figure 2.

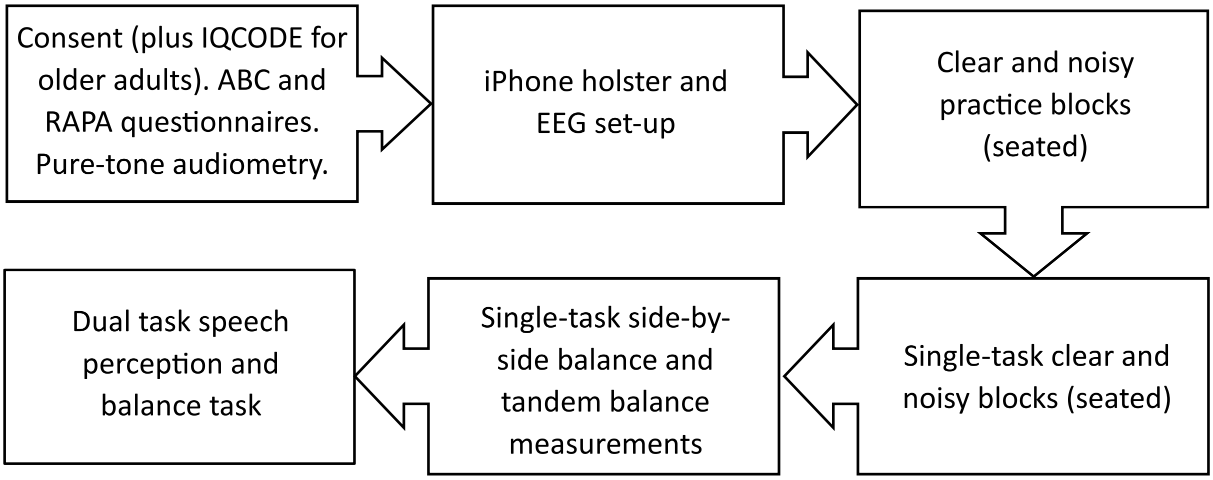


Figure 2. Flowchart detailing the procedure of the study.

5.4.6. Statistical analyses

Data collected in this study were analysed using a series of mixed ANCOVA models in SPSS (IBM SPSS Statistics for Windows, Version 28.0. Armonk, New York) and visualised using R Studio (version 4.2.1), assessing differences between groups and conditions. Pure-tone audiometry was included as a covariate in each statistical model to control for differences in hearing acuity. To correct for multiple models, an alpha value of p=.017 was used as the threshold for significance.

Behavioural data.

Model 1 analysed behavioural data, the outcome variable being the percentage of letters and numbers correctly identified in each condition of the dual-task speech perception block. To do this, the number of letters and numbers correctly identified in each block was first calculated – given that there were 24 trials in each block, the highest possible total correct was 48 (a letter and a number for each trial). This score was then converted to a percentage. As there were two blocks per condition, the two percentages were averaged to provide a grand mean percentage of words correctly identified in each condition. To address the violation of ANOVA assumptions present with percentage data, these grand means were converted into z-scores, following the procedures recommended by Caldwell et al. (2019). A 2 (Age: Younger vs Older) x 2 (Stance: Easy vs Difficult) x 2 (Listening Condition: Clear vs Noisy) mixed ANCOVA was then conducted. Post-hoc pairwise comparisons were also used where appropriate.

Behavioural data: dual-task costs. To analyse the impact that the reallocation of attentional resources to balance maintenance has on speech perception performance, an exploratory analysis was also conducted on the dual-task costs involved in the speech perception task. That is, the difference in the percentage of words correctly identified when participants completed the task seated (single-task condition, no postural manipulation) versus when they completed the task in either the Easy or Hard stance condition (dual-task condition) were computed using the following formula:

$$Dual\ task\ costs = \frac{dual\ task_{\%\ Correct} - single\ task_{\%\ Correct}}{single\ task_{\%Correct}}\ x\ 100$$

This resulted in 4 dual-task cost outcome variables (e.g. the dual-task cost value for EasyClear compared the speech perception performance of participants in the clear listening, easy stance condition compared to the clear listening, seated condition). Dual-task costs were then analysed using a 2 (Age: Younger vs Older) x 2 (Stance: Easy vs Difficult) x 2 (Listening Condition: Clear vs Noisy) mixed ANCOVAs.

EEG data: fronto-central alpha power

The dependent variable for Model 2 was the difference in fronto-central alpha power from baseline. Alpha power recorded over each fronto-central electrode was averaged to produce a grand mean resting alpha power during the fixation cross (1000ms) and a grand mean experimental alpha power during the video clip (3000ms). Mean baseline alpha power was subtracted from mean experimental alpha power, to create a mean fronto-central alpha power difference for each Stance and Listening Condition experimental condition. A 2(Age: Younger vs Older) x 2 (Stance: Easy vs Hard) x 2 (Listening Condition: Clear vs Noisy) mixed ANCOVA was then conducted. Post-hoc pairwise comparisons were also used where appropriate.

EEG data: parieto-occipital alpha power.

The dependent variable for Model 3 was the difference in parieto-occipital alpha power from baseline. Alpha power recorded over each parieto-occipital electrode was averaged to produce a grand mean resting alpha power during the fixation cross (1000ms) and a grand mean experimental alpha power during the video clip (3000ms). Mean baseline alpha power was subtracted from mean experimental alpha power, to create a mean parieto-occipital alpha power difference for each Stance and Listening Condition experimental condition. A 2 (Age: Younger vs Older) x 2 (Stance: Easy vs Hard) x 2 (Listening Condition: Clear vs Noisy) mixed ANCOVA was then conducted. Post-hoc pairwise comparisons were also used where appropriate.

Sway velocity

A further exploratory analysis was conducted on the sway velocities recorded by each participant in each condition. Velocity was recorded (cm/s) in 3 x 60 second segments for each block of each condition. Given that there were two blocks of trials per condition, this resulted in 6 sway velocity segments for each Stance x Listening Condition experimental condition. These velocities were averaged so that each Stance x Listening Condition experimental condition corresponded to one grand mean sway velocity. A 2 (Age: Younger vs Older) x 2 (Stance: Easy vs Difficult) x 2 (Listening Condition: Clear vs Noisy) mixed ANCOVA was then conducted on these grand mean velocity measures.

5.4.7. Deviations from pre-registration

It is important to note that the analyses conducted on the current dataset are not the final sample of participants required for this study to be adequately powered. As such, the results presented should be viewed as preliminary pending the recruitment of the full sample size.

5.5. Results

5.5.1. Behavioural data analysis – dual-task speech perception performance

Behavioural data in this study constitutes the percentage of letters and numbers correctly identified in each dual-task condition. The mean percentage correct, for each age group, is displayed in *Figure 3*.

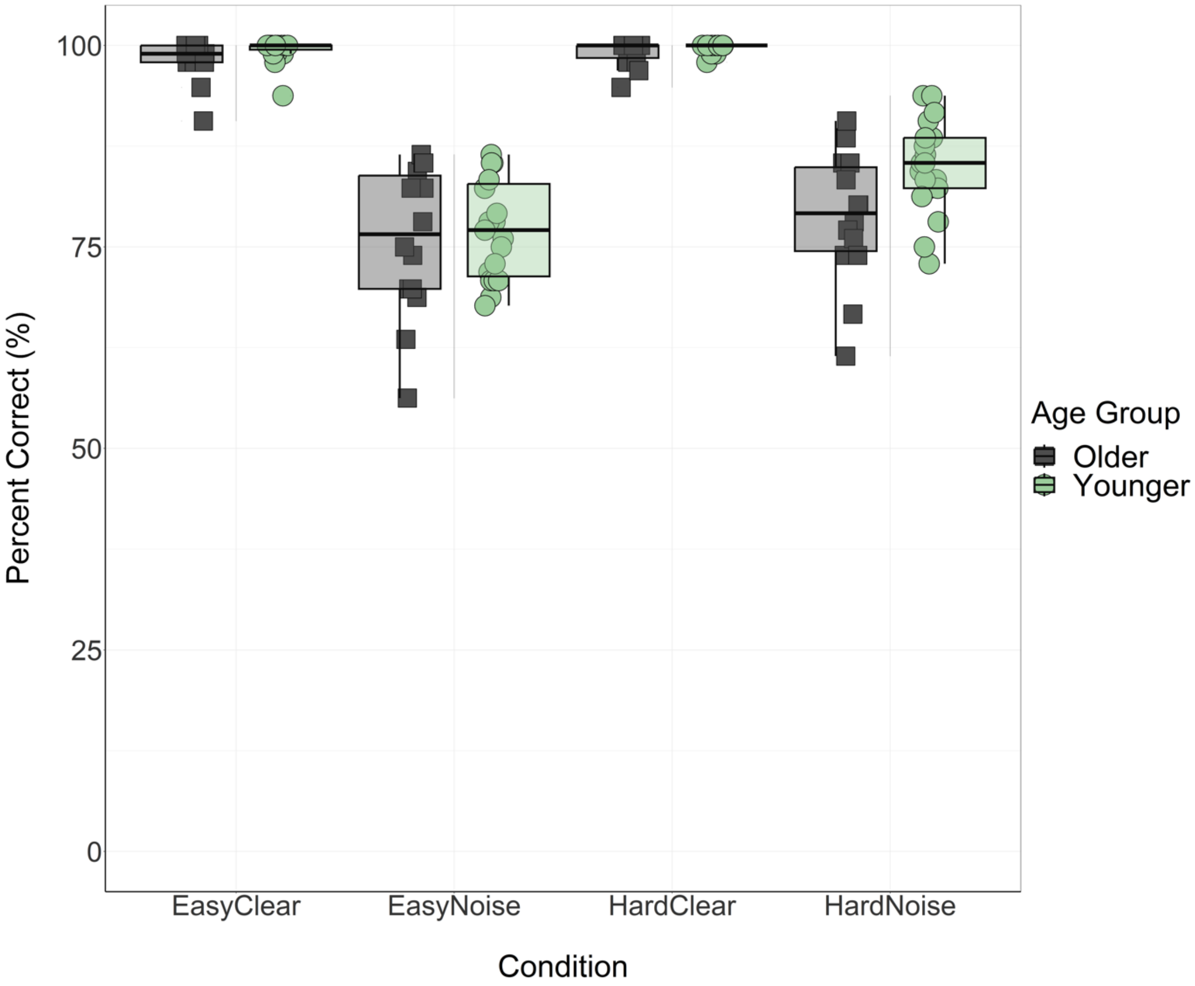


Figure 3. Mean percentage of letters and numbers correctly identified in each condition. Grey squares represent data of older adults, green circles represent data of younger adults.

H1: Older adults' speech perception will be more negatively affected by difficult balance conditions than by easy balance conditions, compared to younger adults.

To analyse participants behavioural responses in the dual-task conditions, a 2 (Age: Younger vs Older) x 2 (Stance: Easy vs Hard) x 2 (Listening Condition: Clear vs Noisy) mixed ANCOVA was conducted. The ANCOVA revealed that there was no significant interaction between Stance and Age [*F*(1,32)=.09, *p*=.770, ηp^2=.003). As a result, the data do not support hypothesis 1 predicting that older adults would produce a weaker speech perception performance compared to younger adults when balance is compromised. For completeness, the rest of the model statistics are as follows. There was also no significant main effect of Age on the percentage of words correctly identified [*F*(1,32 = 0.12, *p*=.733, ηp^2= 0.004)]. Overall, a similar percentage of words were correctly identified by older adults (*M*=88.49%, *SE*=1.09) as by younger adults (*M*=88.90%, *SE*=0.0.96).

However, the mixed ANCOVA did reveal a significant main effect of Stance [(*F*(1,32)= 11.97, *p*=.002, ηp^2=0.27)]. Interestingly, a greater percentage of letters and numbers were correctly identified in the hard stance condition (*M*=90.85%, *SE*=0.53) than in the easy stance condition (*M*=87.54%, *SE*=0.71; mean difference = 3.31%, *SE*=0.57, *p*<.001), in contrast to our predictions that speech perception would be more difficult in challenging balance conditions.

H2: Older adults' speech perception in noisy conditions will be more negatively affected by difficult balance than in clear conditions.

The mixed ANCOVA revealed no significant interaction between Age, Stance and Listening Condition [*F*(1,32)= .096, *p*=.759, ηp^2=.003]. As such, the data currently do not support hypothesis 2. For completeness, the rest of the model statistics are as follows. There was a significant main effect of listening condition on the percentage of words correctly identified [*F*(1,32)=64.28, *p*<.001, ηp^2=.67)]. As would be expected, a greater percentage of words were correctly identified in the clear listening conditions (*M*=99.18%, *SE*=0.24) compared to noisy listening conditions (*M*=79.20%, *SE*=1.01; mean difference = 19.98%, *SE*=0.95, *p*<.001).

It was also important to analyse any interactions between variables, and crucially, the mixed ANCOVA revealed a significant interaction between Stance and Listening Condition [*F*(1,32)=8.62, *p*=.006, ηp^2=0.21). Post-hoc pairwise comparisons revealed that in the clear listening condition, there was no significant difference in the percentage of words correctly identified in the easy stance position (*M*=98.87%, *SE*=0.34) compared to the hard stance position (*M*=99.49%, *SE*=0.19). However, in the noisy listening condition, there was a significant difference; more words were correctly identified in the hard stance position (*M*=82.20%, *SE*=1.02) compared to the easy stance position (*M*=76.21%, *SE*=1.30; mean difference = 6.00%, *SE*=1.17, *p*<.001). This is in partial support of our hypothesis predicting that the impact of the balance manipulation on speech perception will be most evident in the most challenging listening conditions, in which cognitive load is high. However, the results are in the opposite direction to our prediction – in noisy listening conditions, speech perception appears to be improved during the most difficult, tandem balance positions compared to the easy, side-by-side position. Pairwise comparisons also revealed that, in the easy balance position, identification was better in clear listening conditions (*M*=98.87%, *SE*=0.34) compared to noisy listening conditions (*M*=76.21%, *SD*=1.30; mean difference = 22.66%, *SE*=1.25, *p*<.001). Likewise, in the hard balance position, identification was better in clear listening conditions (*M*=99.49%, *SE*=0.19) compared to noisy listening conditions (*M*=82.20%, *SE*=1.02; mean difference = 17.29%, *p*<.001).

There were no significant interactions between Stance and Age [*F*(1,32)=.09, *p*=.770, ηp^2=.003), or between Listening Condition and Age [*F*(1,32)=0.19, *p*=.670, ηp^2=.006]. There was also no significant interaction between Age, Stance and Listening Condition [*F*(1,32)= .096, *p*=.759, ηp^2=.003].

5.5.2. Exploratory behavioural data analysis – dual-task costs

As a further exploratory analysis, dual-task costs were calculated for each participant in each condition. That is, the difference in the percentage of words correctly identified when participants completed the task seated (single-task condition, no postural manipulation) versus when they completed the task in either the Easy or Hard stance position (dual-task condition) were computed using the following formula:

$$Dual\ task\ costs = \frac{dual\ task_{\%\ Correct} - single\ task_{\%\ Correct}}{single\ task_{\%Correct}}\ x\ 100$$

Negative dual-task cost values indicate a decrease in the percentage of words correctly identified, which means a weaker performance in dual-task conditions (i.e. better performance in single-task conditions, as would be expected). Positive values represent an increase in the percentage of words correctly identified in dual-task conditions (i.e. weaker performance in single-task conditions). One participant was removed from these analyses due to producing an anomalously low single-task performance. Dual-task costs produced in each condition of the speech perception task are displayed in *Figure 4*.

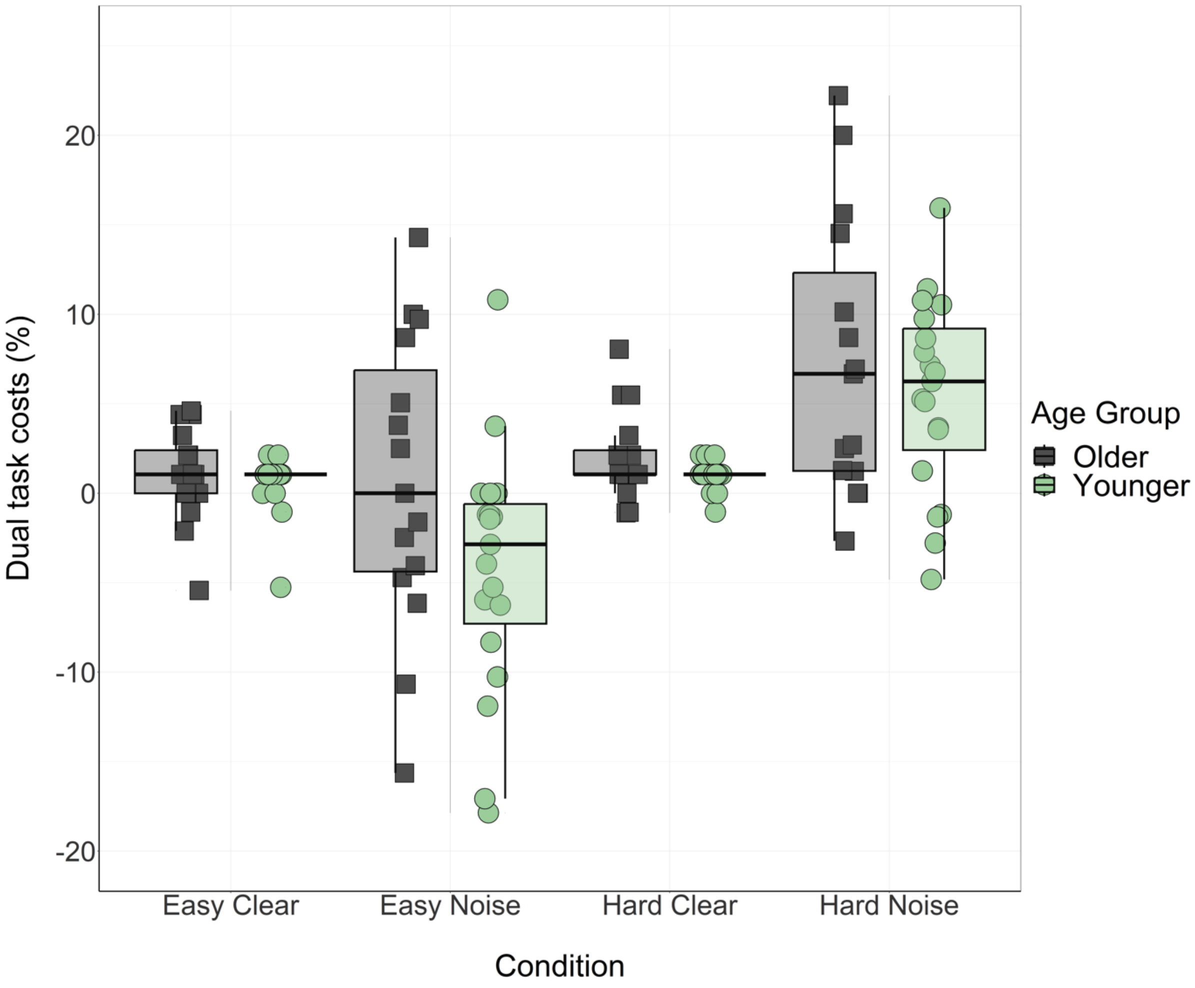


Figure 4. Dual-task costs calculated for percentage of words correctly identified by each participant in each Stance and Listening Condition experimental condition. Grey markers represent data of older adults, green markers represent data of younger adults.

These dual-task costs were analysed using a 2 (Age: Younger vs Older) x 2 (Stance: Easy vs Hard) x 2 (Listening Condition: Clear vs Noisy) mixed ANCOVA. The ANCOVA revealed no significant main effect of Listening Condition [*F*(1, 31) = 2.91, *p*=.098, ηp^2=.086] and no significant interactions between Stance and Age [*F*(1, 31) = 0.40, *p*=.843, ηp^2=.001], Listening Condition and Age [*F*(1, 31)=3.67, *p*=.065, ηp^2=.106], and no three-way interaction between Age, Stance and Listening Condition [*F*(1, 31)=0.092, *p*=.764, ηp^2=.003].

However, the mixed ANCOVA on the dual-cost behavioural data revealed a significant main effect of Stance [*F*(1, 31)=8.94, *p*=.005, ηp^2=.224]. Participants exhibited greater dual-task costs in the Hard stance condition (*M*=4.00, *SE*=0.57) than in the Easy stance condition (*M*=-0.45, *SE*=0.63; mean difference = 4.45, *SE* = 0.78, *p*<.001). Participants exhibited negative dual-task costs in the Easy stance position, indicating that speech perception performance was weaker in the Easy stance position than in the seated position. However, with regards to the Hard stance position, dual-task costs were positive – interestingly, this suggests that participants produced a stronger speech perception performance in the difficult balance position compared to when seated.

The mixed ANCOVA also revealed a significant main effect of Age [*F*(1, 31)=8.78, *p*=.006, ηp^2=0.221]. Greater dual-task costs were exhibited by older adults (*M*=3.81, *SE*=0.89) than by younger adults (*M*=-0.27, *SE*=0.75; mean difference = 1.38, *SE*=1.38, *p*=.006). However, looking at the directions of these costs, it appears that younger adults produced a stronger performance in the single-task conditions than in the dual-task conditions, whereas older adults correctly identified more words in the dual-task conditions overall than in the single-task conditions.

Finally, the mixed ANCOVA on dual-task costs revealed a significant interaction between Stance and Listening Condition [*F*(1, 31)=6.63, *p*=.015, ηp^2=0.176]. Post-hoc pairwise comparisons revealed that in the Easy stance condition, there was no significant difference in dual-task costs produced in clear (*M*=0.75, *SE*=0.36) or noisy listening conditions (*M*=-1.66, *SE*=1.31; mean difference = 2.40, *SE*=1.46, *p*=.110). However, in the Hard stance condition, greater dual task costs were exhibited in noisy listening conditions (*M*=6.66, *SE*=1.10) compared to clear listening conditions (*M*=1.33, *SE*=0.24; mean difference = 5.33, *SE*=1.13, *p*<.001). Once again, it is important to note that in contrast to our hypotheses, performance in the Hard stance, noisy dual-task conditions was stronger than in the seated, noisy single-task conditions.

Post-hoc comparisons also revealed that in clear listening conditions, greater dual-task costs were exhibited in the Hard stance condition (*M*=1.33, *SE*=0.24) than in the Easy stance condition (*M*=0.75, *SE*=0.36; mean difference = 0.58, *SE*=0.28*, p*=.047). The means of these reflected that performance was stronger in clear dual-task conditions than in clear single-task conditions. In addition, in the noisy listening condition, greater dual-task costs were exhibited in the Hard stance condition (*M*=6.66, *SE*=1.10) than in the Easy stance conditions (*M*=-1.66, *SE*=1.31; mean difference = 8.32, *SE*=1.57, *p*<.001). This suggests that speech perception performance was worse in Easy stance, noisy conditions compared to seated, noisy conditions, whilst performance was better in Hard stance, noisy conditions than in seated, noisy conditions.

5.5.3. EEG data analysis – fronto-central alpha power

H3: Participants will display decreased fronto-central alpha power in difficult balance conditions compared to easy balance conditions.

The difference from baseline in fronto-central alpha power was analysed using a 2 (Age: Younger vs Older) x 2 (Stance: Easy vs Hard) x 2 (Listening Condition: Clear vs Noisy) mixed ANCOVA. The ANCOVA revealed no significant main effects of Stance [*F*(1,32) = 2.61, *p*=.116, ηp^2=.074]. As a result, the data did not support hypothesis three predicting that participants will display decreased fronto-central alpha power in difficult balance conditions compared to easy balance conditions. For completeness, the rest of the model statistics are as follows.

There was also no significant main effect of Age [*F*(1, 32) = 0.30, *p*=.586, ηp^2=.009], and no significant interactions between Listening Condition and Age [*F*(1,32) = 1.98, *p*=.169, ηp^2=.058], between Stance and Listening Condition [*F*(1, 32) = 0.52, *p*=.475, ηp^2=0.016], or in the three-way interaction between Age, Stance and Listening Condition [*F*(1, 32) = 0.01, *p*=.921, ηp^2=0.00]. However, the mixed ANCOVA did reveal a significant main effect of Listening Condition [*F*(1, 32) = 7.68, *p*=.009, ηp^2=0.19]. The decrease from baseline in fronto-central alpha power was greater in clear listening condition (*M*=-0.44, *SE* = 0.10) than in the noisy listening condition (*M*=-0.27, *SE*=0.07; mean difference = 0.17, *SE*=0.06, *p*=.012); potential reasons for this are postulated in the Discussion section.

H4: Older adults will produce larger decreases in fronto-central alpha power than younger adults in difficult balance conditions.

The mixed ANOVA revealed no significant interactions between Stance and Age [*F*(1, 32) = 0.0004, *p*=.985, ηp^2=.00]. This means that the data did not support hypothesis four predicting age-related differences in fronto-central alpha power as a result of manipulating balance demands.

5.5.4. EEG data analysis – parieto-occipital alpha power

H5: Participants will show increased parieto-occipital alpha power in noisy listening conditions compared to clear listening conditions.

Difference from baseline in parieto-occipital alpha power was analysed using a 2 (Age: Younger vs Older) x 2 (Stance: Easy vs Hard) x 2 (Listening Condition: Clear vs Noisy) mixed ANCOVA. The mixed ANCOVA revealed no significant main effect of Listening Condition [*F*(1, 32)=0.001, *p*=.976, ηp^2=.00]. The data therefore do not support hypothesis five that parieto-occipital alpha power would increase in challenging speech perception conditions. There were also no significant main effects of Stance [*F*(1, 32) = 4.00, *p*=.054, ηp^2=0.11] or Age [*F*(1,32)=0.005, *p*=.946, ηp^2=.00].

H6: Older adults will display smaller increases in parieto-occipital alpha power during noisy listening conditions than younger adults

There were no significant interactions between Age and Listening Condition [*F*(1, 32)=1.23, *p*=.276, ηp^2=0.04]. As a result, the data do not support hypothesis six predicting that older adults will display smaller increases in parieto-occipital alpha power during noisy listening conditions than younger adults. There were also no significant interactions between Age and Stance [*F*(1, 32)=0.07, *p*=.790, ηp^2=.002], between Stance and Listening Condition [*F*(1, 32)=0.05, *p*=.825, ηp^2=.002], and no significant three-way interaction between Age, Stance and Listening Condition [*F*(1, 32)=0.09, *p*=.770, ηp^2=.003].

5.5.5. Balance Assessments

Exploratory analyses were conducted to ascertain the balance ability of the younger and older participants within the study. With regards to the sway velocity recorded in each of the dual-task conditions, there was no significant main effect of Listening Condition [*F*(1,32)=0.36, *p*=.555, np^2=0.01] and no significant main effect of Age [*F*(1,32)=0.42, *p*=.520, np^2=0.01]. There were also no significant interactions between Stance and Listening Condition [*F*(1,32)=1.16, *p*=.289, np^2=0.04], between Age and Listening Condition [*F*(1,32)=0.064, *p*=.802, np²=.002), and no significant three way interaction between Age, Stance and Listening Condition [*F*(1,32)=.002, *p*=.962, np²=.00]. However, there was a significant main effect of Stance [*F*(1,32)=7.71, *p*=,009, np²=.19] – all participants displayed a greater sway velocity in hard balance conditions (*M*=48.60, *SE*=3.72) compared to easy balance conditions (*M*=31.50, *SE*=2.17; mean difference = 17.10, *SE* = 21.6, *p*<.001). Sway velocities for each participant, in each dual-task condition, are displayed in *Figure 5*.

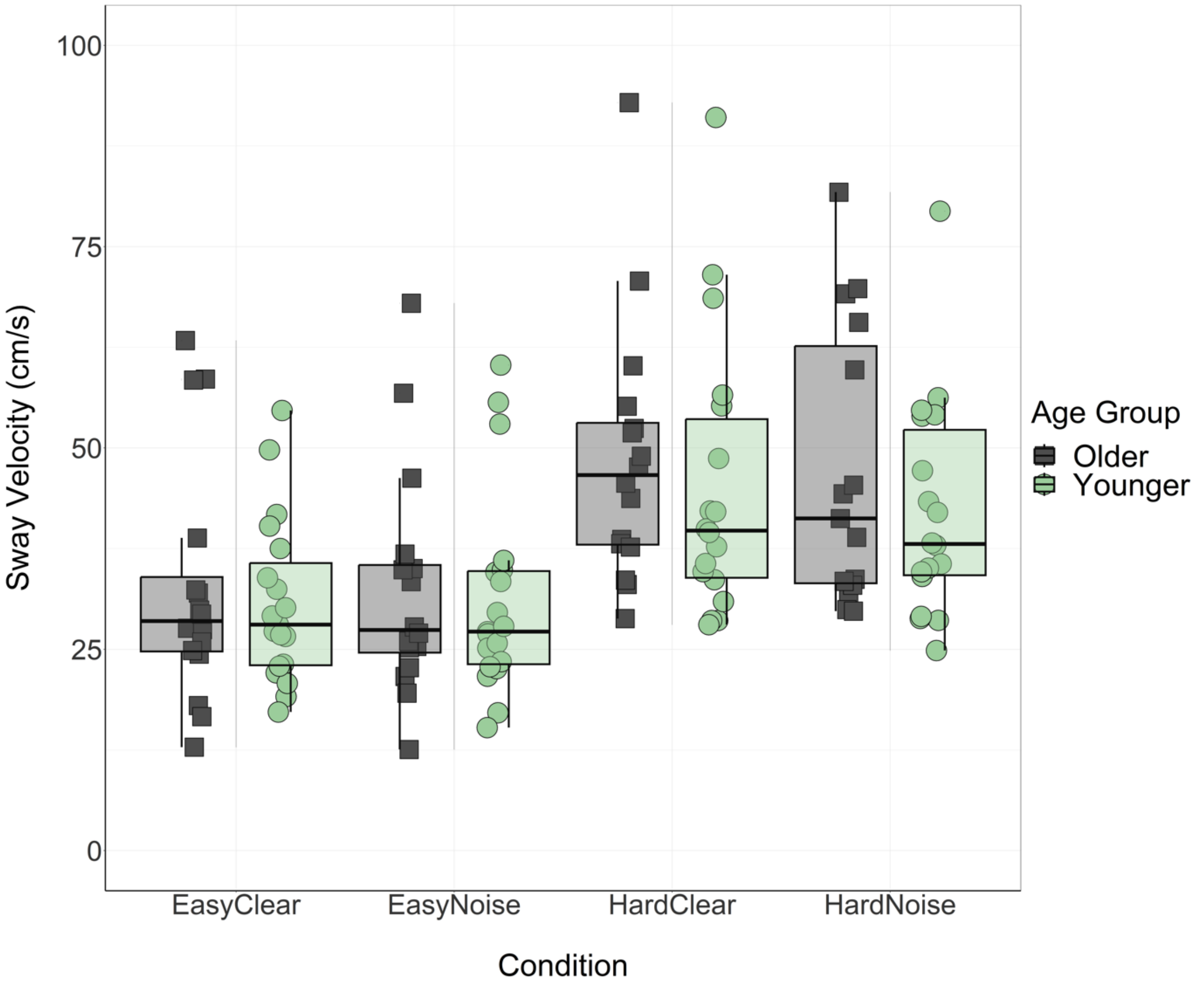


Figure 5. Mean sway velocity, in cm/s, of each participant in each of the dual-task conditions. Grey squares represent data of older adults, green circles represent data of younger adults.

Participants also completed the Activities-Based Balance Confidence scale (ABC) and the Rapid Assessment of Physical Activity (RAPA) as a subjective measure of their physical status.

Independent *t*-tests revealed no significant differences in ABC scores [*t*(33)=-0.68, *p*=.502] – a similar balance confidence was reported by younger adults (*M*=94.70, *SD*=5.12) as by older adults (*M*=95.82, *SD*=4.55). However, there was a significant difference in total RAPA scores [*t*(33)=-2.70, *p*=.011] – interestingly, a higher total RAPA score (i.e. higher physical activity level) was reported by older adults (*M*=8.25, *SD*=1.81) compared to younger adults (*M*=6.05, *SD*=2.80; mean difference = 2.20, *SE*=0.81).

5.6. Discussion

The aim of this study was to investigate whether age-related changes in oscillatory alpha power reflect the allocation of attentional resources during dual-task speech perception and balance maintenance. Behavioural data confirmed previous research indicating that, for all ages, speech perception is significantly more difficult in adverse listening conditions, underlining the challenges that are encountered in our noisy, dynamic everyday lives when we need to listen to and understand speech. Whilst fluctuations in parieto-occipital alpha power were non-significant, analysis of fronto-central alpha power alongside behavioural data suggest that younger and older adults' speech perception performance may, surprisingly, be preserved when cognitive load is high. That is, across age groups, standing in a hard balance position improved speech perception under noisy listening conditions, compared to the easy balance position. In addition, for older adults, speech perception performance was actually stronger in the dual-task conditions compared to single-task conditions. Taken together, these findings may reveal important insights into allocation of attentional resources during dual-task balance and speech perception, and could indicate that older adults may be more robust to age-related changes in attentional control than once thought.

Younger and older adults displayed similar dual-task speech perception performances.

Previous literature suggests that older adults experience increased difficulties with speech perception compared to younger adults (Tremblay et al., 2021; Helfer et al., 2017, Roberts & Allen, 2016), particularly in noisy listening conditions. This is, in part, due to deteriorations in sensory processing such as age-related hearing loss throughout the peripheral auditory system (e.g. degeneration of hair cells in the cochlea, atrophy of spiral ganglion cells; Slade et al., 2020). In addition, older adults find it more difficult than younger adults to inhibit background noise (Hasher et al., 2007; Borghini et al., 2018; Gazzaley et al., 2005; Gazzaley et al., 2008; Fabiani et al., 2006) during audiovisual speech perception, processing more task-irrelevant, distracting information which increases cognitive load and weakens the ability to perceive the speech signal.

However, the non-significant main effect of Age in the dual-task behavioural analyses, and the fact that Age does not significantly interact with any other independent variable within this test, does not support previous research indicating that older adults experience difficulties with speech perception compared to younger adults. Given that age-related deficits in speech perception, particularly under high cognitive load, is such an established finding in the field, the non-significant finding may reflect a lack of power. Equal samples of younger and older adults, and more participants in total, may produce results in line with previous research indicating that older adults experience increased difficulties in perceiving speech in adverse or cognitively-demanding listening conditions.

However, a key consideration with regards to the current sample is the individual differences between older adults that may improve their top-down ability to flexibly allocate attentional resources. That is, in line with the "cognitive reserve" theory of ageing (Stern et al., 2020), external factors in the lives of each older participant may allow them to compensate for age-related declines in attentional control during audiovisual integration. These external factors, such as educational, social, cognitive and physical activities, accumulate "cognitive reserve" in older adults (Stern et al., 2020; Oosterhuis et al., 2023), which increases cognitive flexibility by facilitating the use of cognitive strategies, strengthening existing brain networks or recruiting different brain regions altogether (Oosterhuis et al., 2023). With regards to audiovisual speech perception in adverse listening conditions, older adults with high cognitive reserve may be able to compensate for deficits in inhibiting background noise or age-related hearing loss by using a different strategy, such as allocating more attentional resources to visual inputs, for example (Rosemann & Thiel, 2018; Puschmann et al., 2014; Puschmann & Thiel, 2017; Pepper & Nuttall, 2023). In addition, individuals with high cognitive reserve may be more effective in dividing attentional resources between two concurrent multisensory tasks. Taken together, it is important to consider the cognitive reserve levels of the sample when studying the potential impact of age-related changes in attentional control on speech perception and balance maintenance.

The sample of older adults used in the current study were likely to have high cognitive reserve. For example, many of the older participants were recruited from the Centre for Ageing Research Panel at Lancaster University and from University of the Third Age, two groups of older adults who remain engaged in education and are motivated to learn more about the ageing process. In addition, questionnaire data indicated that older adults were more physically active than the younger adults in this study. As such, despite the fact that this study did not involve calculating a composite cognitive reserve "score", it is fair to suggest that the increased educational involvement and increased physical activity levels of our older participants may result in them having higher cognitive reserve compared to older adults who are more cognitively and physically frail. Having high cognitive reserve could explain how these older adults were able to flexibly allocate attentional resources between speech perception and balance maintenance, producing a similar performance to younger adults. It is important that future studies a) implement measures of cognitive reserve to build a comprehensive account of the cognitive abilities of their older adult sample, and b) increase the diversity of older adults recruited to participate in neuroscientific research, to produce results that may be more representative of the attentional abilities of the entire population.

Speech perception performance was stronger in difficult balance positions during noisy listening conditions.

We hypothesised that a significant interaction would exist between Stance and Listening Condition, in that differences in dual-task speech perception performance would only be evident during noisy listening conditions due to high cognitive load. Whilst this significant interaction did exist in the current data, the pattern of results was opposite to our expectations. As predicted, in clear listening conditions, speech perception performance was similar across Easy and Hard stance conditions. However, in noisy listening conditions, participants correctly identified a greater percentage of words in the Hard stance position than in the Easy stance position. This suggests that in a complex acoustic environment like that experienced in the noisy listening conditions, a challenging balance task may improve performance in the simultaneous speech perception task.

Whilst this finding may seem counterintuitive, similar theories have been discussed in previous literature usually in the context of postural control, and have been attributed to an important attentional mechanism known as "anchoring" (Deviterne et al., 2005). That is, more complex acoustic conditions have actually been found to reduce postural sway during easy and hard balance conditions (Helfer et al., 2020; Gandemer et al., 2017; Ross et al., 2016; Deviterne et al., 2005), with sound serving as an "anchor" or orienting signal to enhance balance (Heifer et al., 2020). If this is the case in the current study, and the complex, noisy listening condition was relied upon as an anchor to maintain balance in the Hard stance position, perhaps this had a knock-on effect on speech perception performance – allocating more attentional resources to the audiovisual information in the noisy listening conditions may have simultaneously stabilised balance and improved speech perception performance. This is supported by the fact that there was no significant main effect of Listening Condition on sway velocity – balance was not negatively affected by the adverse listening conditions, which may indicate that the complex auditory information in the noisy listening condition actually facilitated balance maintenance to the extent that sway was equivalent across clear and noisy listening conditions.

As well as providing interesting insights into how speech perception may be preserved in dual-task conditions, these findings could also have important implications for treatments and therapies to improve balance in older adults who may be at increased risk of falls. For example, many cognitive therapies focus on teaching older adults to attend to relevant information and inhibit task-irrelevant information to reduce distractibility during balance (van het Reve & de Bruin, 2014; Smith-Ray et al., 2015). Instead, perhaps balance could be strengthened through dual-task training (Halvarsson et al., 2015), teaching older adults how to efficiently allocate attentional resources and to effectively utilise external, seemingly task-irrelevant sensory information as anchor points in their environment, improving orientation and reducing fall risk.

Younger and older adults exhibited differing patterns of dual-task costs in speech perception performance.

The exploratory analysis on the dual-task cost data revealed an interesting difference between younger and older adults in single-task speech perception performance compared to dual-task speech perception performance. Younger adults produced a pattern of results that would be expected: more words were correctly identified in the single-task seated condition – in which there was no postural manipulation so attention could be focussed on audiovisual integration for speech perception – compared to the dual-task condition. However, for older adults, a stronger performance was produced in the dual-task conditions compared to the single-task conditions, even though attentional resources were being competed for; in theory, dual-task attentional demands should have had a detrimental effect on both speech perception and balance ability in older adults (Helfer et al., 2020; Ruffieux et al., 2015; Lajoie et al., 2005).

A potential reason for this could be the motivation displayed by older adults compared to younger adults throughout the task. Indeed, recent discussions from Ryan & Campbell (2021) highlighted that older adults are often extremely motivated for the duration of neurocognitive experiments, enthusiastic about measuring or improving their cognitive health, contributing to science, and exhibiting more curiosity about the experiment compared to younger adults (Ryan & Campbell, 2021; Frank et al., 2015). Further theories posit that highly motivated older adults may engage more cognitive resources during a difficult task to avoid confirming preconceived negative stereotypes surrounding ageing, challenging such stereotypes by producing a strong perceptual performance (Todd Maddox & Markman, 2010; Hess et al., 2019). Older adults therefore may have acknowledged how much more cognitively challenging the postural manipulation made the task compared to seated conditions, and allocated increased attentional resources to the audiovisual video clip to preserve speech perception performance in light of this. This is facilitated by the fact that the older adults in this study were very fit and able (as indicated by their RAPA scores; see below), so were feasibly able to reallocate attentional resources to speech perception in this way without compromising their balance performance. In contrast, younger adults may feel less inclined to "prove" their balance and speech perception abilities (Ryan & Campbell, 2021) and therefore exhibit a lower baseline motivation, demonstrating greater dual-task costs. Future research should acknowledge the different motivations that younger and older adults may have for participating in neurocognitive research and consider how this may impact performance in any cognitively-demanding task.

Fronto-central alpha power was similar across stance positions and age groups, but there was a significant difference between listening conditions.

In contrast to our hypotheses, there were no significant differences in fronto-central alpha power between Easy and Hard stance conditions, or across age groups. Previous literature has found decreases in fronto-central alpha power under challenging balance conditions (Kahya et al., 2022; Hulsdunker et al., 2015; Del Percio et al., 2009; Slobounov et al., 2009; Beurskens et al., 2016), particularly in older adults (Edwards et al., 2018) – this is indicative of increased involvement of cortical motor regions for balance in healthy ageing, due to age-related neurodegeneration of subcortical balance centres (Ozdemir et al., 2016). In the current study, the fact that there was no significant main effect of Age or Stance on fronto-central alpha power may reflect the high physical activity levels of the participants in this study. Indeed, the older adult sample actually produced a significantly higher RAPA score than the younger adults in the sample, highlighting the older adults' strong cardiorespiratory and strength-based physical ability. Younger and older adults also exhibited equal balance confidence, as measured by the ABC scale. If these older adults are fit, healthy, and confident in their balance, dual-task balance maintenance may still be a relatively automatic process for them like it is for younger adults, requiring fewer cognitive-motor or attentional resources compared to older adults who may be more cognitively and physically frail (Edwards et al., 2018; Shaw, et al., 2018; Kahya et al., 2022). As a result, balance maintenance may not be reflected in fronto-central alpha activity as the older adults in the current sample do not need to recruit an increased amount of cortical resources to postural control. However, this does not explain why there was no significant main effect of Stance in the current data; perhaps future research, implementing an even more challenging balance manipulation (e.g. proprioceptive perturbation through standing on foam; Anson et al., 2019) with less active participant groups, may uncover how the allocation of attentional resources towards balance maintenance is reflected in fronto-central alpha power.

Despite the fact that there was no significant main effect of Stance on fronto-central alpha power, there was a significant main effect of Listening Condition – all participants showed greater decreases from baseline in clear listening conditions compared to noisy listening conditions. Whilst there were originally no hypotheses surrounding this, it could be a further indication of the "anchoring" effect of complex auditory information, discussed earlier (Helfer et al., 2020; Ross et al., 2016; Easton et al., 1998). That is, if the complex, noisy listening environment stabilised balance through acting as an orienting point (i.e. rendering the Hard stance condition less challenging), cortical motor regions may not be as essential for balance maintenance. In contrast, if the speech perception task is less "anchoring" due to the simpler auditory stimuli in the clear conditions, more cortical resources are required to maintain balance, which may be reflected in greater decreases in fronto-central alpha power compared to noisy condition.

Parieto-occipital alpha activity did not differ between clear and noisy listening conditions.

In contrast to our hypotheses, manipulating the cognitive load of participants by adding challenging background noise to the speech perception task was not reflected by increases in parieto-occipital alpha power. These data do not support the findings of previous literature, which indicates that in order to inhibit distracting background noise, parieto-occipital alpha power increases during audiovisual integration to prevent the task-irrelevant noise being incorporated into the percept. In this study, it is likely that the non-significant difference between clear and noisy listening conditions may be due to the small sample size at present. Indeed, it is well-established that parietal brain regions, in particular, exhibit increased alpha power when task-irrelevant auditory information is difficult to ignore (Wostmann et al., 2017).

Perhaps in the current study, despite the high signal-to-noise ratio rendering the task acoustically challenging, the background noise being semantically different to the target sentences made it slightly easier to inhibit (Diaz et al., 2019; Murphy et al., 2018). That is, the 4-talker random background sentences that participants had to ignore (e.g. "squirrels live in trees", "tomato soup is a liquid") had different phonetic and semantic properties to the target sentences that participants were focusing on attending to (e.g. "place blue at C2 soon"). Due to these differences between both stimuli, participants may have experienced less informational masking and may have therefore found it easier to segregate the auditory streams and ignore the background noise (Schneider & Daneman, 2007; Ben-David et al., 2012). This could be a potential reason behind the non-significant increases in parieto-occipital alpha power. Future research paradigms may benefit from implementing task-irrelevant sentences that are both structurally different and structurally similar to the target speech (Diaz et al., 2019; Murphy et al., 2018), to compare the impact that easy-to-ignore and difficult-to-ignore irrelevant speech has on parieto-occipital alpha power, and how this changes with healthy ageing.

5.7. Conclusion

To conclude, the ability to allocate attentional resources between two co-occurring tasks is key for successful performance in speech perception and balance maintenance during our dynamic, multisensory everyday lives. Whilst previous research suggests that older adults may produce weaker performances in these dual-task scenarios due to increased cognitive load, the current study did not find such age-related changes. This potentially highlights the high cognitive and physical abilities of the older adult sample and emphasises the impact that individual differences in cognitive flexibility may have on attentional allocation across the lifespan. Investigating age-related changes in fronto-central and parieto-occipital alpha power remains a promising way to determine the neural correlates of attentional control for balance maintenance and audiovisual speech perception, with larger and more diverse participant samples likely to reveal significant differences between groups. Nevertheless, from these preliminary data, we have observed that the attentional abilities of older adults may be more robust than anticipated, utilising the complex sensory information available to them in their environment to serve as an anchor point for balance, which in turn may improve perceptual performance in tasks like speech perception.

References

Anson, E., Studenski, S., Sparto, P. J., & Agrawal, Y. (2019). Community-dwelling adults with a history of falling report lower perceived postural stability during a foam eyes closed test than non-fallers. *Experimental brain research*, *237*, 769-776.

Begau, A., Klatt, L. I., Schneider, D., Wascher, E., & Getzmann, S. (2022). The role of informational content of visual speech in an audiovisual cocktail party: Evidence from cortical oscillations in young and old participants. *European Journal of Neuroscience*, *56*(8), 5215-5234.

Ben-David, B. M., Vania, Y. Y., & Schneider, B. A. (2012). Does it take older adults longer than younger adults to perceptually segregate a speech target from a background masker?. *Hearing research*, *290*(1-2), 55-63.

Beurskens, R., Steinberg, F., Antoniewicz, F., Wolff, W., & Granacher, U. (2016). Neural correlates of dual-task walking: Effects of cognitive versus motor interference in young adults. *Neural plasticity*, *2016*(1), 8032180.

Boisgontier, M. P., & Nougier, V. (2013). Ageing of internal models: from a continuous to an intermittent proprioceptive control of movement. *Age*, *35*, 1339-1355.

Boisgontier, M. P., Beets, I. A., Duysens, J., Nieuwboer, A., Krampe, R. T., & Swinnen, S. P. (2013). Age-related differences in attentional cost associated with postural dual tasks: increased recruitment of generic cognitive resources in older adults. *Neuroscience & Biobehavioral Reviews*, *37*(8), 1824-1837.

Borghini, G., Candini, M., Filannino, C., Hussain, M., Walsh, V., Romei, V., ... & Cappelletti, M. (2018). Alpha oscillations are causally linked to inhibitory abilities in ageing. *Journal of Neuroscience*, *38*(18), 4418-4429.

Brauer, S. G., Woollacott, M., & Shumway-Cook, A. (2002). The influence of a concurrent cognitive task on the compensatory stepping response to a perturbation in balance-impaired and healthy elders. *Gait & posture*, *15*(1), 83-93.

Caldwell, J. A., Niro, P. J., Farina, E. K., McClung, J. P., Caron, G. R., & Lieberman, H. R. (2019). A Z-score based method for comparing the relative sensitivity of behavioral and physiological metrics including cognitive performance, mood, and hormone levels. *Plos one*, *14*(8), e0220749.

Callis, N. (2016). Falls prevention: Identification of predictive fall risk factors. *Applied nursing research*, *29*, 53-58.

Campos, J., Ramkhalawansingh, R., & Pichora-Fuller, M. K. (2018). Hearing, self-motion perception, mobility, and aging. *Hearing research*, *369*, 42-55.

Cooke, M., Barker, J., Cunningham, S., & Shao, X. (2006). An audio-visual corpus for speech perception and automatic speech recognition. *The Journal of the Acoustical Society of America*, *120*(5), 2421-2424.

Daskalopoulou, C., Koukounari, A., Wu, Y. T., Terrera, G. M., Caballero, F. F., De La Fuente, J., ... & Prina, M. (2019). Healthy ageing trajectories and lifestyle behaviour: the Mexican Health and Aging Study. *Scientific Reports*, *9*(1), 11041.

Del Percio, C., Babiloni, C., Bertollo, M., Marzano, N., Iacoboni, M., Infarinato, F., ... & Eusebi, F. (2009). Visuo-attentional and sensorimotor alpha rhythms are related to visuo-motor performance in athletes. *Human brain mapping*, *30*(11), 3527-3540.

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of neuroscience methods*, *134*(1), 9-21.

Delorme, A., Sejnowski, T., & Makeig, S. (2007). Enhanced detection of artifacts in EEG data using higher-order statistics and independent component analysis. *Neuroimage*, *34*(4), 1443-1449.

Deviterne, D., Gauchard, G. C., Jamet, M., Vançon, G., & Perrin, P. P. (2005). Added cognitive load through rotary auditory stimulation can improve the quality of postural control in the elderly. *Brain research bulletin*, *64*(6), 487-492.

Dey, A., & Sommers, M. S. (2015). Age-related differences in inhibitory control predict audiovisual speech perception. *Psychology and aging*, *30*(3), 634.

Diaz, M. T., Johnson, M. A., Burke, D. M., Truong, T. K., & Madden, D. J. (2019). Age-related differences in the neural bases of phonological and semantic processes in the context of task-irrelevant information. *Cognitive, Affective, & Behavioral Neuroscience*, *19*, 829-844.

Doshi, K. B., Moon, S. H., Whitaker, M. D., & Lockhart, T. E. (2023). Assessment of gait and posture characteristics using a smartphone wearable system for persons with osteoporosis with and without falls. *Scientific reports*, *13*(1), 538.

Easton, R. D., Greene, A. J., DiZio, P., & Lackner, J. R. (1998). Auditory cues for orientation and postural control in sighted and congenitally blind people. *Experimental brain research*, *118*, 541-550.

Edwards, A. E., Guven, O., Furman, M. D., Arshad, Q., & Bronstein, A. M. (2018). Electroencephalographic correlates of continuous postural tasks of increasing difficulty. *Neuroscience*, *395*, 35-48.

Eriksson, S., Gustafson, Y., & Lundin-Olsson, L. (2008). Risk factors for falls in people with and without a diagnose of dementia living in residential care facilities: a prospective study. *Archives of gerontology and geriatrics*, *46*(3), 293-306.

Fabiani, M., Low, K. A., Wee, E., Sable, J. J., & Gratton, G. (2006). Reduced suppression or labile memory? Mechanisms of inefficient filtering of irrelevant information in older adults. *Journal of cognitive neuroscience*, *18*(4), 637-650.

Frank, D. J., Nara, B., Zavagnin, M., Touron, D. R., & Kane, M. J. (2015). Validating older adults' reports of less mind-wandering: An examination of eye movements and dispositional influences. *Psychology and Aging*, *30*(2), 266.

Franse, C. B., van Grieken, A., Qin, L., Melis, R. J., Rietjens, J. A., & Raat, H. (2017). Socioeconomic inequalities in frailty and frailty components among community-dwelling older citizens. *PloS one*, *12*(11), e0187946.

Franzen, L., Delis, I., De Sousa, G., Kayser, C., & Philiastides, M. G. (2020). Auditory information enhances post-sensory visual evidence during rapid multisensory decision-making. *Nature communications*, *11*(1), 5440.

Gandemer, L., Parseihian, G., Kronland-Martinet, R., & Bourdin, C. (2017). Spatial cues provided by sound improve postural stabilization: evidence of a spatial auditory map?. *Frontiers in neuroscience*, *11*, 357.

Gazzaley, A., Clapp, W., Kelley, J., McEvoy, K., Knight, R. T., & D'Esposito, M. (2008). Age-related top-down suppression deficit in the early stages of cortical visual memory processing. *Proceedings of the National Academy of Sciences*, *105*(35), 13122-13126.

Gazzaley, A., Cooney, J. W., McEvoy, K., Knight, R. T., & D'esposito, M. (2005). Top-down enhancement and suppression of the magnitude and speed of neural activity. *Journal of cognitive neuroscience*, *17*(3), 507-517.

Getzmann, S., Golob, E. J., & Wascher, E. (2016). Focused and divided attention in a simulated cocktail-party situation: ERP evidence from younger and older adults. *Neurobiology of aging*, *41*, 138-149.

Goble, D. J., Coxon, J. P., Van Impe, A., De Vos, J., Wenderoth, N., & Swinnen, S. P. (2010). The neural control of bimanual movements in the elderly: Brain regions exhibiting age-related increases in activity, frequency-induced neural modulation, and task-specific compensatory recruitment. *Human brain mapping*, *31*(8), 1281-1295.

Graetzer, S., Akeroyd, M. A., Barker, J., Cox, T. J., Culling, J. F., Naylor, G., ... & Viveros-Muñoz, R. (2022). Dataset of British English speech recordings for psychoacoustics and speech processing research: The clarity speech corpus. *Data in brief*, *41*, 107951.

Halvarsson, A., Franzén, E., & Ståhle, A. (2015). Balance training with multi-task exercises improves fall-related self-efficacy, gait, balance performance and physical function in older adults with osteoporosis: a randomized controlled trial. *Clinical rehabilitation*, *29*(4), 365-375.

Hasher, L., Lustig, C., & Zacks, R. T. (2007). Inhibitory mechanisms and the control of attention. *Variation in working memory*, *19*, 227-249.

Hegeman, J., Weerdesteyn, V., van den Bemt, B., Nienhuis, B., van Limbeek, J., & Duysens, J. (2012). Dual-tasking interferes with obstacle avoidance reactions in healthy seniors. *Gait & posture*, *36*(2), 236-240.

Helfer, K. S., Freyman, R. L., van Emmerik, R., & Banks, J. (2020). Postural control while listening in younger and middle-aged adults. *Ear and hearing*, *41*(5), 1383-1396.

Helfer, K. S., Merchant, G. R., & Wasiuk, P. A. (2017). Age-related changes in objective and subjective speech perception in complex listening environments. *Journal of Speech, Language, and Hearing Research*, *60*(10), 3009-3018.

Hess, T. M., Growney, C. M., & Lothary, A. F. (2019). Motivation moderates the impact of aging stereotypes on effort expenditure. *Psychology and Aging*, *34*(1), 56.

British Society of Audiology. (2024). *Recommended Procedure: Pure-tone air-conduction and bone-conduction threshold audiometry with and without masking*. https://www.thebsa.org.uk/wp-content/uploads/2023/10/OD104-32-Recommended-Procedure-Pure-Tone-Audiometry-August-2018-FINAL-1.pdf

Hülsdünker, T., Mierau, A., & Strüder, H. K. (2016). Higher balance task demands are associated with an increase in individual alpha peak frequency. *Frontiers in human neuroscience*, *9*, 695.

Hülsdünker, T.; Mierau, A.; Neeb, C.; Kleinöder, H.; Strüder, H. Cortical processes associated with continuous balance control as revealed by EEG spectral power. Neurosci. Lett. 2015, 592, 1–5.

Iersel, M. B. V., Kessels, R. P., Bloem, B. R., Verbeek, A. L., & Olde Rikkert, M. G. (2008). Executive functions are associated with gait and balance in community-living elderly people. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *63*(12), 1344-1349.

Jansen, A. P., van Hout, H. P., Nijpels, G., van Marwijk, H. W., Gundy, C., de Vet, H. C., & Stalman, W. A. (2008). Self-reports on the IQCODE in older adults: a psychometric evaluation. *Journal of geriatric psychiatry and neurology*, *21*(2), 83-92.

Jorm, A. F. (2004). The Informant Questionnaire on cognitive decline in the elderly (IQCODE): a review. *International psychogeriatrics*, *16*(3), 275-293.

Kahya, M., Gouskova, N. A., Lo, O. Y., Zhou, J., Cappon, D., Finnerty, E., ... & Manor, B. (2022). Brain activity during dual-task standing in older adults. *Journal of NeuroEngineering and Rehabilitation*, *19*(1), 123.

Kahya, M., Moon, S., Ranchet, M., Vukas, R. R., Lyons, K. E., Pahwa, R., ... & Devos, H. (2019). Brain activity during dual task gait and balance in aging and age-related neurodegenerative conditions: a systematic review. *Experimental gerontology*, *128*, 110756.

Keil, J., & Senkowski, D. (2017). Individual alpha frequency relates to the sound-induced flash illusion. *Multisensory Research*, *30*(6), 565-578.

Keil, J., & Senkowski, D. (2018). Neural oscillations orchestrate multisensory processing. *The Neuroscientist*, *24*(6), 609-626.

Keller, A. S., Payne, L., & Sekuler, R. (2017). Characterizing the roles of alpha and theta oscillations in multisensory attention. *Neuropsychologia*, *99*, 48-63.

Kelly, S. P., Lalor, E. C., Reilly, R. B., & Foxe, J. J. (2006). Increases in alpha oscillatory power reflect an active retinotopic mechanism for distracter suppression during sustained visuospatial attention. *Journal of neurophysiology*, *95*(6), 3844-3851.

Klatt, L. I., Schneider, D., Schubert, A. L., Hanenberg, C., Lewald, J., Wascher, E., & Getzmann, S. (2020). Unraveling the relation between EEG correlates of attentional orienting and sound localization performance: a diffusion model approach. *Journal of Cognitive Neuroscience*, *32*(5), 945-962.

Lajoie, Y., & Gallagher, S. P. (2004). Predicting falls within the elderly community: comparison of postural sway, reaction time, the Berg balance scale and the Activities-specific Balance Confidence (ABC) scale for comparing fallers and non-fallers. *Archives of gerontology and geriatrics*, *38*(1), 11-26.

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1993). Attentional demands for static and dynamic equilibrium. *Experimental brain research*, *97*, 139-144.

Lakens, D., & Caldwell, A. R. (2019). Simulation-based power-analysis for factorial ANOVA designs.

Lange, J., Keil, J., Schnitzler, A., van Dijk, H., & Weisz, N. (2014). The role of alpha oscillations for illusory perception. *Behavioural brain research*, *271*, 294-301.

Li, L. Y. J., Wang, S. Y., Wu, C. J., Tsai, C. Y., Wu, T. F., & Lin, Y. S. (2020). Screening for hearing impairment in older adults by smartphone-based audiometry, self-perception, HHIE screening questionnaire, and free-field voice test: comparative evaluation of the screening accuracy with standard pure-tone audiometry. *JMIR mHealth and uHealth*, *8*(10), e17213.

Lim, S. K., & Kong, S. (2022). Prevalence, physical characteristics, and fall risk in older adults with and without possible sarcopenia. *Aging clinical and experimental research*, *34*(6), 1365-1371.

Montero-Odasso, M., Verghese, J., Beauchet, O., & Hausdorff, J. M. (2012). Gait and cognition: a complementary approach to understanding brain function and the risk of falling. *Journal of the American Geriatrics Society*, *60*(11), 2127-2136.

Murphy, D. R., Bailey, H., Pearson, M., & Albert, G. (2018). The irrelevant speech effect among younger and older adults: The influence of background noises on reading comprehension. *Experimental aging research*, *44*(2), 162-178.

Oosterhuis, E. J., Slade, K., May, P. J. C., & Nuttall, H. E. (2023). Toward an understanding of healthy cognitive aging: the importance of lifestyle in cognitive reserve and the scaffolding theory of aging and cognition. *The Journals of Gerontology: Series B*, *78*(5), 777-788.

O'Sullivan, A. E., Lim, C. Y., & Lalor, E. C. (2019). Look at me when I'm talking to you: Selective attention at a multisensory cocktail party can be decoded using stimulus reconstruction and alpha power modulations. *European Journal of Neuroscience*, *50*(8), 3282-3295.

Ozdemir, R. A., Contreras-Vidal, J. L., Lee, B. C., & Paloski, W. H. (2016). Cortical activity modulations underlying age-related performance differences during posture–cognition dual tasking. *Experimental brain research*, *234*, 3321-3334.

Pepper, J. L., & Nuttall, H. E. (2023). Age-related changes to multisensory integration and audiovisual speech perception. *Brain Sciences*, *13*(8), 1126.

Powell, L. E., & Myers, A. M. (1995). The activities-specific balance confidence (ABC) scale. *The journals of Gerontology Series A: Biological sciences and Medical sciences*, *50*(1), M28-M34.

Puschmann, S., & Thiel, C. M. (2017). Changed crossmodal functional connectivity in older adults with hearing loss. *Cortex*, *86*, 109-122.

Puschmann, S., Sandmann, P., Bendixen, A., & Thiel, C. M. (2014). Age-related hearing loss increases cross-modal distractibility. *Hearing Research*, *316*, 28-36.

Reed-Jones, R. J., Solis, G. R., Lawson, K. A., Loya, A. M., Cude-Islas, D., & Berger, C. S. (2013). Vision and falls: a multidisciplinary review of the contributions of visual impairment to falls among older adults. *Maturitas*, *75*(1), 22-28.

Rihs, T. A., Michel, C. M., & Thut, G. (2007). Mechanisms of selective inhibition in visual spatial attention are indexed by α-band EEG synchronization. *European Journal of Neuroscience*, *25*(2), 603-610.

Roberts, K. L., & Allen, H. A. (2016). Perception and cognition in the ageing brain: A brief review of the short-and long-term links between perceptual and cognitive decline. *Frontiers in aging neuroscience*, *8*, 39.

Rosemann, S., & Thiel, C. M. (2018). Audio-visual speech processing in age-related hearing loss: Stronger integration and increased frontal lobe recruitment. *Neuroimage*, *175*, 425-437.

Ross, J. M., Will, O. J., McGann, Z., & Balasubramaniam, R. (2016). Auditory white noise reduces age-related fluctuations in balance. *Neuroscience letters*, *630*, 216-221.

Rosso, A. L., Cenciarini, M., Sparto, P. J., Loughlin, P. J., Furman, J. M., & Huppert, T. J. (2017). Neuroimaging of an attention demanding dual-task during dynamic postural control. *Gait & posture*, *57*, 193-198.

Ruffieux, J., Keller, M., Lauber, B., & Taube, W. (2015). Changes in standing and walking performance under dual-task conditions across the lifespan. *Sports Medicine*, *45*, 1739-1758.

Ryan, A. D., & Campbell, K. L. (2021). The ironic effect of older adults' increased task motivation: Implications for neurocognitive aging. *Psychonomic Bulletin & Review*, *28*(6), 1743-1754.

Schneider, B. A., Li, L., & Daneman, M. (2007). How competing speech interferes with speech comprehension in everyday listening situations. *Journal of the American Academy of Audiology*, *18*(07), 559-572.

Setti, A., Burke, K. E., Kenny, R. A., & Newell, F. N. (2011). Is inefficient multisensory processing associated with falls in older people?. *Experimental brain research*, *209*, 375-384.

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Measurement of attentional reserve and mental effort for cognitive workload assessment under various task demands during dual-task walking. *Biological psychology*, *134*, 39-51.

Slade, K., Beat, A., Taylor, J., Plack, C. J., & Nuttall, H. E. (2024). The effect of motor resource suppression on speech perception in noise in younger and older listeners: An online study. *Psychonomic Bulletin & Review*, *31*(1), 389-400.

Slade, K., Plack, C. J., & Nuttall, H. E. (2020). The effects of age-related hearing loss on the brain and cognitive function. *Trends in Neurosciences*, *43*(10), 810-821.

Slobounov, S., Cao, C., Jaiswal, N., & Newell, K. M. (2009). Neural basis of postural instability identified by VTC and EEG. *Experimental brain research*, *199*, 1-16.

Smith-Ray, R. L., Hughes, S. L., Prohaska, T. R., Little, D. M., Jurivich, D. A., & Hedeker, D. (2015). Impact of cognitive training on balance and gait in older adults. *Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *70*(3), 357-366.

Stern, Y., Arenaza-Urquijo, E. M., Bartrés-Faz, D., Belleville, S., Cantilon, M., Chetelat, G., ... & Reserve, Resilience and Protective Factors PIA Empirical Definitions and Conceptual Frameworks Workgroup. (2020). Whitepaper: Defining and investigating cognitive reserve, brain reserve, and brain maintenance. *Alzheimer's & Dementia*, *16*(9), 1305-1311.

Tan, V., Chen, C., & Merchant, R. A. (2022). Association of social determinants of health with frailty, cognitive impairment, and self-rated health among older adults. *PLoS One*, *17*(11), e0277290.

Thomas, N. M., Bampouras, T. M., Donovan, T., & Dewhurst, S. (2016). Eye movements affect postural control in young and older females. *Frontiers in aging neuroscience*, *8*, 216.

Thut, G., Nietzel, A., Brandt, S. A., & Pascual-Leone, A. (2006). α-Band electroencephalographic activity over occipital cortex indexes visuospatial attention bias and predicts visual target detection. *Journal of Neuroscience*, *26*(37), 9494-9502.

Todd Maddox, W., & Markman, A. B. (2010). The motivation–cognition interface in learning and decision making. *Current Directions in Psychological Science*, *19*(2), 106-110.

Topolski, T. D., LoGerfo, J., Patrick, D. L., Williams, B., Walwick, J., & Patrick, M. M. B. (2006). Peer reviewed: the Rapid Assessment of Physical Activity (RAPA) among older adults. *Preventing chronic disease*, *3*(4).

Tremblay, P., Brisson, V., & Deschamps, I. (2021). Brain aging and speech perception: Effects of background noise and talker variability. *NeuroImage*, *227*, 117675.

van Het Reve, E., & de Bruin, E. D. (2014). Strength-balance supplemented with computerized cognitive training to improve dual task gait and divided attention in older adults: a multicenter randomized-controlled trial. *BMC geriatrics*, *14*, 1-15.

Wajda, D. A., Mirelman, A., Hausdorff, J. M., & Sosnoff, J. J. (2017). Intervention modalities for targeting cognitive-motor interference in individuals with neurodegenerative disease: a systematic review. *Expert review of neurotherapeutics*, *17*(3), 251-261.

Weissgerber, T., Müller, C., Stöver, T., & Baumann, U. (2022). Age differences in speech perception in noise and sound localization in individuals with subjective normal hearing. *Frontiers in psychology*, *13*, 845285.

Wingfield, A. (2016). Evolution of models of working memory and cognitive resources. *Ear and hearing*, *37*, 35S-43S.

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait & posture*, *16*(1), 1-14.

Wöstmann, M., Lim, S. J., & Obleser, J. (2017). The human neural alpha response to speech is a proxy of attentional control. *Cerebral cortex*, *27*(6), 3307-3317.

6. Entraining Alpha Oscillations to Facilitate Auditory Working Memory: A TMS-EEG Study

6.1. Linking Statement

Earlier chapters in this thesis have investigated oscillatory alpha activity with regards to attention and inhibition during audiovisual integration. Instead, Chapter 6 focuses on parietal and auditory alpha power during unisensory auditory processing, in which target speech must be attended to and distracting speech must be inhibited. Previous research suggests that auditory alpha activity may be associated with facilitating attention to target speech, whilst parietal alpha activity may be associated with the inhibition of background noise (Wostmann et al., 2017; Dimitrijevic et al., 2017; Obleser et al., 2012). If older adults experience declines in auditory working memory, exhibiting increased difficulty with perceiving speech amongst background noise, perhaps modulating alpha activity through non-invasive brain stimulation could improve older adults' speech perception. To this end, 32 younger and 32 older adults completed the irrelevant speech paradigm (Wostmann et al., 2017) with task-irrelevant speech that was either easy to ignore or difficult to ignore. Throughout the task, parietal and auditory brain regions were stimulated using TMS set at each participant's individual alpha frequency. The aim of this study was to investigate whether entraining alpha oscillations in these brain regions can impact younger and older adults' ability to inhibit irrelevant auditory information and attend to target speech.

Author note: *The study hypotheses, design and statistical analyses were pre-registered online on the Open Science Framework: https://osf.io/npy9a. This manuscript was prepared in* *collaboration with Dr Kate Slade, Dr Elise Oosterhuis, Dr Bjorn Herrmann, Dr Ingrid Johnsrude, and Dr Helen Nuttall.*

6.2. Abstract

Age-related declines in top-down mechanisms like auditory working memory and attentional control can have a significant impact on an older adult's ability to perceive speech. These declines may be reflected in oscillatory alpha-band activity, associated with attending to relevant speech and inhibiting distracting speech. As such, enhancing alpha activity via transcranial magnetic stimulation (TMS) may improve an older adult's ability to attend to relevant speech signals and inhibit background speech. This study aimed to determine if TMS delivered at an individual alpha frequency (alpha-TMS) benefits auditory working memory, and how this may be affected by age.

Thirty-two younger adults (18-35 years old) and thirty-two older adults (60-80 years old) were asked to attend to and remember a sequence of spoken digits, whilst inhibiting an irrelevant sentence which was either easy to ignore or difficult to ignore. Before the to-be-ignored sentences, participants received alpha-TMS to the vertex, parietal cortex and auditory cortex. The proportion of digits recalled in the correct order, as well as parietal and auditory alpha power during the attending and maintenance of the digits, were compared across conditions and age groups.

Behavioural findings supported previous research suggesting that distracting speech that is high in acoustic detail has a negative impact on the ability to attend to and retain target speech. However, there were no significant differences in auditory working memory performance between younger and older adults, potentially indicative of the strategies relied upon by older adults to compensate for age-related declines in auditory processing. Crucially, from analysing alpha power, it was found that alpha-TMS can successfully entrain parietal and auditory alpha oscillators. The potential benefits of implementing alpha-TMS in future research are discussed, as well as the impact this may have on establishing brain-behaviour links between age-related changes in alpha power and auditory working memory.

Word count: 297

Key words: alpha, entrainment, auditory, inhibition, attention, working memory, ageing

6.3. Introduction

6.3.1. Age-related changes in speech perception

The ability to perceive speech in conversational environments is dependent on both bottom-up and top-down mechanisms. From a bottom-up perspective, we process the auditory signals through the transduction of sound through the auditory pathway, from the ear to the brain; this acoustic signal is then translated in the temporal lobe within the ventral stream of speech processing (Hickok & Poeppel, 2007; Rauschecker & Scott, 2009). According to neurobiological models of speech perception, primary auditory cortex is responsible for decoding the acoustic features of speech, whilst higher-order temporal areas such as the superior temporal gyri are key for processing the intelligibility of speech (Davis & Johnsrude, 2003; Nuttall et al., 2016). Crucially, from a top-down perspective, this influx of auditory information must be modulated; as such, complex cognitive mechanisms like auditory working memory and attentional control are relied upon to select and retain auditory inputs that are task-relevant and to inhibit the processing of task-irrelevant background speech (Millman & Mattys, 2017; Jumar et al., 2016; Serences & Kastner, 2014; Pichora-Fuller et al., 2017; Meister et al., 2013).

For example, when talking to a friend in a noisy restaurant, we need to attend to the words that they are speaking, hold this information in memory, and suppress any distracting, irrelevant noise from background speakers, reverberations, or external factors like traffic noise. Auditory working memory describes how short-term memory is used whilst under cognitive load, responsible for the temporary storage and manipulation of auditory information for use in cognitive tasks (Draheim et al., 2022; Baddeley, 2000; Kaiser et al., 2015; Cowan et al., 1998). For example, in speech perception, words must be held in auditory working memory until their meaning can be interpreted in the context of the rest of the sentence (Cowan et al., 1998). Given that this memory system has a limited capacity, strong attentional mechanisms are required to regulate which auditory inputs are attended to and maintained, and which inputs are suppressed (Draheim et al., 2022). Attentional control is defined as the maintenance of task-relevant information and the filtering or suppression of task-irrelevant information (Draheim et al., 2022). Within the context of speech perception, auditory working memory and attentional control are therefore inherently linked, coordinating to modulate the top-down processing of auditory information during speech perception (Wostmann et al., 2015; Awh et al., 2006).

It has been well-established in previous research that older adults experience increased difficulty in perceiving speech in adverse listening environments (Tremblay et al., 2021; Pichora-Fuller et al., 2017; Getzmann et al., 2016). Not only is this a consequence of the deterioration of peripheral sensory function that comes with healthy ageing (Liberman & Kujawa, 2017; Peelle et al., 2011; Anderson et al., 2013), but is also due to difficulties in the ability to attend to and retain relevant target speech, and inhibit irrelevant, distracting background noise (Pepper & Nuttall, 2023; Wostmann et al., 2017; Gazzaley et al., 2005). Indeed, the ageing process results in declines in auditory processing in older adults even without hearing loss, and in situations where there is no background noise (Grose & Mamo, 2010; Harris et al., 2012; Anderson et al., 2013), highlighting the importance of higher-level cognitive functions such as auditory working memory and inhibition in deciphering the speech signal. Age-related difficulties in perceiving speech can have a significant impact on an older adult's quality of life, with many feeling reluctant to visit noisy environments and withdrawing from social situations, leading to loneliness and depression (Lawrence et al., 2020; Cosh et al., 2019). Given our increasingly ageing population, and the fact that both auditory working memory and attentional control are susceptible to declines with healthy ageing, it is key that we understand how the age-related changes in these top-down mechanisms impact speech perception across the lifespan.

6.3.2. Oscillatory alpha activity in speech perception

Evidence suggests that the top-down mechanisms involved in perceiving speech may be reflected in neural oscillations in the alpha-band frequency (8-12Hz; Wostmann et al., 2015; Wostmann et al., 2017). Despite previously being referred to as "idling" rhythms associated with resting brain states, evidence suggests that alpha activity can reflect attentional control and inhibitory mechanisms (Lange et al., 2014; Kelly et al., 2006; Pepper & Nuttall, 2023). Crucially, an inverse relationship exists between alpha power and brain activity – lower alpha power is associated with greater neural activation in a certain brain region (i.e. lower inhibition), and higher alpha power is associated with lesser neural activation (i.e. higher inhibition; Shaw et al., 2018). Analysing patterns in alpha activity may therefore provide key insights into the neural mechanisms of attention and inhibition during speech perception.

Alpha-band activity has been studied in relation to speech perception in challenging listening environments. The predominant view is that increases in alpha activity reflect increased inhibition, with alpha synchronisation being observed in speech-in-noise perception and during effortful listening when background noise is distracting and must be suppressed (McMahon et al., 2016; Dimitrijevic et al., 2019). This increased inhibition of task-irrelevant auditory information should therefore increase the availability of attentional resources for the processing of target speech (Jensen & Mazaheri, 2010). However, alternative theories posit that, instead of reflecting inhibitory control, decreases in alpha activity instead may directly facilitate attention towards target speech (Seifi Ala et al., 2020). This is supported by research finding that in difficult listening conditions, alpha power decreased when target speech had to be attended to and retained in memory (Seifi Ala et al., 2020; Dimitrijevic et al., 2017). As such, there is active debate within the field with regards to the exact functional role of alpha activity during attentive listening, and where such activity originates from. That is, if alpha is key for inhibiting task-irrelevant sensory information, it is likely to be driven by domain-general (i.e. non-auditory) brain regions involved in attentional networks (Wostmann et al., 2017). However, if the main functional role of alpha is to facilitate the processing of target speech, then perhaps it may be driven by domain-specific (i.e. auditory) brain regions within the temporal cortex (Dimitrijevic et al., 2017).

Alpha power in non-auditory brain regions may reflect the higher-level cognitive processes involved in speech perception, such as auditory working memory and inhibition; much of the research in this area has focussed on alpha oscillators in the parietal cortex (Dimitrijevic et al., 2017; Wostmann et al., 2017). For example, after implementing an irrelevant-speech paradigm with younger adults, Wostmann et al. (2017) found that highly distracting background speech (i.e. irrelevant speech high in acoustic detail) evoked larger increases in alpha power in domain-general parietal regions, compared to less distracting background speech that is easier to inhibit. This indicates that the greater the effort required to suppress distracting information, the greater the parietal alpha power (Wostmann et al., 2017; Wostmann et al., 2015; Obleser et al., 2012; Wisniewski et al., 2017; Peterson et al., 2015). In addition, Dimitrijevic et al. (2017) found increased alpha power across central and parietal regions in younger adults during a speech-in-noise task, in which distracting background noise had to be suppressed. Taken together, there is strong evidence to suggest that increases in parietal alpha power reflect the increased ability to inhibit distracting sensory information.

Whereas increases in parietal alpha power are believed to reflect inhibition of distracting information, decreases in alpha power in domain-specific, auditory brain regions may represent neural activation to facilitate attention towards target speech. Indeed, Dimitrijevic et al. (2017) found that in temporal regions associated with auditory cortex, participants showed a significant relationship between decreased alpha power and improved speech perception performance. However, research into the patterns of auditory alpha activity appears to be mixed, in that Obleser et al. (2012) and Van Dijk et al. (2010) found that auditory alpha power, instead, increased during challenging auditory tasks and memory tasks. As such, further research is required to determine how increases or decreases in alpha power in parietal and auditory brain regions can impact speech perception in challenging listening conditions.

6.3.3. Age-related changes in oscillatory alpha activity

It is also important to note that much of the research in this field is based on younger adult participants – given the age-related declines in the top-down mechanisms involved in speech perception (Pepper & Nuttall, 2023; Getzmann et al., 2017; Getzmann et al., 2016), it is crucial to investigate how alpha power may change as a function of healthy ageing. From the limited research that does exist, the main differences between younger and older adults appear to be related to parietal alpha power – specifically, Wostmann et al. (2015) found that older adults demonstrated reduced parietal alpha power compared to younger adults during speech-in-noise perception. If greater increases in parietal alpha power reflects strong inhibition, then the reduced alpha power exhibited by older adults could be an underlying cause of their weaker inhibitory abilities (Henry et al., 2017; Wostmann et al., 2015; Sander et al., 2012). In other words, perhaps parietal alpha oscillators are less effective for inhibition in older adults compared to younger adults.

Further theories surrounding the age-related changes in oscillatory alpha activity suggest that perhaps younger and older adults use different strategies to perceive speech. For example, Herrmann et al. (2022) posited that whilst parietal alpha dominates in younger adults, auditory alpha may dominate in older adults. That is, if parietal alpha oscillators are less involved in the listening process for older adults, perhaps a compensatory strategy is employed which sees an increased engagement of auditory alpha oscillators, to preserve auditory working memory performance by facilitating attention to target speech (Hermann et al., 2022). Taken together, it is clear that further research is required to unpick the dynamic interplay between alpha power in different brain regions and how it associates with age-related changes in speech perception performance.

Regardless of whether alpha activity during listening is driven by domain-specific or domain-general brain regions, enhancing alpha activity via neuromodulation may serve as a promising intervention to improve the speech perception abilities of older adults. Specifically, the role of alpha activity in auditory working memory and inhibition, and how this changes as a function of healthy ageing, can be investigated using transcranial magnetic stimulation (TMS) and electroencephalography (EEG) in conjunction. By measuring each participant's individual alpha frequency (IAF; the frequency at which alpha power is at its maximal) and stimulating the parietal cortex and auditory cortex at this frequency, it may be possible to entrain alpha oscillators in each brain region (Thut et al., 2011; Zaehle et al., 2010). Indeed, previous research has suggested that TMS set at a participant's IAF (herein referred to as alpha-TMS) can be used to reproduce an entrainment signature. Thut et al. (2011) described this kind of entrainment as the induction of a neural signature with a topography and frequency that replicates the naturally-occurring oscillation, which is enhanced throughout the TMS train of pulses. This entrainment drives existing, endogenous brain oscillations, rather than generating new artificial rhythms. If alpha-TMS can reproduce natural alpha oscillations to enhance alpha activity, this could be a key mechanism by which alpha-TMS can functionally modulate perceptual performance (Thut et al., 2011).

TMS-EEG combinations can therefore be highly useful to draw causal links between entraining parietal and auditory alpha oscillators and measuring the impact that such stimulation has on behavioural performance in a speech perception task. That is, if reduced parietal alpha power is the underlying reason behind the difficulties that older adults may have with inhibiting distracting background noise, then using alpha-TMS to enhance parietal alpha activity during listening may improve an older adult's inhibitory abilities during speech perception (see Zoefel & Davis, 2017, for similar discussions surrounding the utility of non-invasive brain stimulation). Likewise, entraining alpha oscillators in auditory regions could answer whether increases (Obleser et al., 2012; Van Dijk et al., 2010) in auditory alpha power impacts the facilitation of attention to target speech. Taken together, TMS-EEG combinations can be used to investigate a) mechanisms by which non-invasive brain stimulation works to modulate neural oscillations in different frequency bands and b) the functional role of alpha activity in everyday tasks like speech perception.

6.3.4. Cross-frequency coupling – alpha-gamma oscillations

It may also be important to consider how neural oscillations from different frequency bands work together to facilitate quick and accurate speech perception – specifically, whether oscillations in the gamma-band frequency (>30Hz) are modulated by alpha activity (Glim et al., 2019; Roux et al., 2013; Canolty & Knight, 2010) during listening. Previous research suggests that oscillations in the gamma-band are associated with the bottom-up processing of sensory information (Keil & Senkowski, 2018). Indeed, lower gamma-band power (approximately 30Hz-48Hz) is associated with decoding the temporal fine structure of the speech signal, rendering it a key neural oscillation in bottom-up auditory processing (Rufener et al., 2016). Previous research suggests that auditory stimuli evoke a gamma response at approximately 40Hz, associated with central processes involved in extracting the meaning of sound, like perceptual organisation of an auditory stream (Noda et al., 2013; Ross & Fujioka, 2016), and neural timing (Nikolic et al., 2013; Buzsaki & Wang, 2012). Such perceptual organisation is inherently linked to auditory working memory and inhibition – the ability to retain and recall target speech is dependent upon its perceived structure (Noyce et al., 2024). Whilst interactions between alpha and gamma have been heavily researched within the visual domain (Jensen et al., 2014; Tzvi et al., 2018, Van Kerkoerle et al., 2014; Daume et al., 2017), there is less evidence available as to the impact of such interactions in the auditory domain. Furthering our understanding of alpha-gamma interactions in audition will shed light on how oscillations from different frequency bands may coordinate to facilitate the processing of target speech and inhibit distracting background speech, and how such coupling may change with healthy ageing.

If parietal alpha oscillations are associated with inhibition, then it would be reasonable to suggest that increases in parietal alpha power will result in decreases in parietal gamma power, reducing the processing of the bottom-up auditory signal. Likewise, if auditory alpha oscillations are associated with attention to target speech, then perhaps reduced alpha power may correlate with increased gamma activity, facilitating the processing of the bottom-up auditory signal. In other words, the interplay between bottom-up and top-down mechanisms in speech perception could be investigated through analysing alpha-gamma power-power interactions (Menceloglu et al., 2020). This interplay may be key for modulating which sensory inputs are suppressed or processed further, and how this may change with healthy ageing. If, through neuromodulation, alpha-gamma interactions can be enhanced in older adults (Reinhart & Nguyen, 2019), perhaps this could be an effective way to strengthen the top-down speech perception of our ageing population, facilitating auditory working memory to modulate bottom-up sensory processing when target speech needs to be attended to and background speech needs to be inhibited.

The current study aimed to investigate whether entraining parietal and auditory alpha oscillations in younger and older adults can facilitate auditory working memory. Younger and older adults completed an auditory working memory task (Wostmann et al., 2017), in which the task-irrelevant speech was either low distractibility (easy to ignore) or high distractibility (difficult to ignore). Participants completed these tasks whilst receiving repetitive TMS (rTMS) set at their individual alpha frequency. This alpha-TMS was administered to the auditory cortex, the parietal cortex and the vertex (as a control site), to investigate how entraining alpha oscillators in auditory and parietal regions can impact auditory working memory and attentional control during speech perception.

Behavioural responses from the task reflected participants' ability to attend to, maintain and recall target auditory information, and the ability to inhibit distracting background speech. Neural responses reflected alpha power in auditory and parietal cortices during the attendance and maintenance of target speech and inhibition of irrelevant background noise. In addition, alpha-gamma cross-frequency coupling in younger and older adults during speech perception was analysed, to explore the impact of entraining alpha oscillators on the relationship between alpha power and gamma power in parietal and auditory regions, and how this may change with healthy ageing. The hypotheses for the study were as follows:

Behavioural hypotheses:

1. If alpha entrainment supports wider auditory working memory processes, such as target facilitation and maintenance, performance will be similarly enhanced in both distractibility conditions after alpha-TMS, compared to distractibility conditions after vertex alpha-TMS.
2. If alpha entrainment supports inhibition of irrelevant information, performance will be enhanced in the most distracting task condition compared to the least distracting condition after alpha-TMS.
3. If alpha entrainment supports different functional roles depending on age, there will be an interaction between age group, task condition, and alpha-TMS condition.
4. If domain-general parietal alpha oscillators moderate task performance, then performance will be maximally enhanced in the parietal alpha-TMS condition, relative to the auditory and the vertex alpha-TMS conditions.
5. If domain-specific auditory alpha oscillators moderate task performance, then performance will be maximally enhanced in the auditory alpha-TMS condition, relative to the parietal and the vertex alpha-TMS conditions.
6. If the dominant oscillator during task performance changes with age, there will be interaction between age group and alpha-TMS condition.

Neural hypotheses:

1. If alpha-TMS can entrain alpha oscillators in parietal brain regions, parietal alpha power will be higher after alpha-TMS to parietal regions compared to alpha-TMS to the vertex.
2. If alpha-TMS can entrain alpha oscillators in auditory brain regions, auditory alpha power will be higher after alpha-TMS to auditory regions compared to alpha-TMS to the vertex.
3. Exploratory neural hypothesis: If alpha-TMS can entrain alpha oscillators in parietal and auditory brain regions, this will result in reduced gamma power in both brain regions.
4. Exploratory neural hypothesis: If older adults experience difficulties with auditory working memory, older adults will exhibit weaker alpha-gamma coupling compared to younger adults.

This experiment was pre-registered prior to data collection on Open Science Framework: https://osf.io/npy9a

6.4. Methods

6.4.1. Participants

This study included a total of 64 participants; 32 younger adults (15 males, 15 females, 2 non-binary) between 18-30 years old (M_{Age} = 20.78, *SD* = 2.59) and 32 older adults (13 males, 19 females) between 60-80 years old (M_{Age} = 68.38, *SD* = 5.01). Sample size was determined via an a-priori power analysis using the wp.kanova package in R studio (see pre-registration on Open Science Framework: https://osf.io/npy9a. The wp.kanova package was implemented as recommended for ANOVA analyses (Zhang et al., 2018), using the large effect sizes that have been found in previous related literature (Wostmann et al., 2017), a Cohen's f value of 0.4, an alpha significance level of 0.05, and a power of 80%. This yielded a minimum sample size of 64, in order to detect interaction effects between TMS location, Distractibility condition and age.

Participants were eligible for the study if they were right-handed, monolingual English speakers with normal or corrected-to-normal vision, screened for via self-report. Participants were ineligible to proceed with the experiment if they had a history or current diagnosis of language disorders (e.g. dyslexia), neurological conditions (e.g. epilepsy, mild cognitive impairment, Parkinson's disease) or psychiatric disorders (e.g. depression, schizophrenia, bipolar disorder). Participants were also ineligible to participate in the experiment if they had any non-removable in their body close to their head (e.g. cochlear implant, cardiac pacemaker).

Participants were recruited via opportunity sampling; younger participants were students at Lancaster University, whilst older participants were recruited via the Centre for Ageing Research at Lancaster University and local community groups such as University of the

Third age, or through word of mouth. All participants provided informed consent. Participants presented no TMS contraindications on the day of the testing session as assessed by the Lancaster University TMS safety screening form (based on guidelines from Rossi et al., 2009).

6.4.2. Pre-screening

Informant Questionnaire on Cognitive Decline in the Elderly (IQ-CODE; Jorm, 2004; Appendix B)

In order to screen for mild cognitive impairment, older adult participants completed a self-report version of the Informant Questionnaire on Cognitive Decline in the Elderly (IQ-CODE; Jorm, 2004; Appendix A) to rate how their current performance in certain everyday tasks has changed compared to 10 years ago, answering on a 5-point Likert scale (1="Much improved", 5="Much worse"). An average score of 3.65 was used as a cut-off point to evaluate mild cognitive impairment and dementia (Jansen et al., 2008), therefore people whose average score was higher than 3.65 were not eligible to participate in the experiment. This was to ensure that any differences in auditory working memory measured in the task were not due to the participant experiencing mild cognitive impairment. The mean IQ-CODE score of older adults in this study was 3.13 (*SD*=0.18).

Pure-Tone Audiometry Assessment (British Society of Audiology, 2018)

Pure-tone audiometric (PTA) hearing thresholds were established using a diagnostic audiometer (Amplivox Model 270 Diagnostic Audiometer, Amplivox Ltsd, UK) in accordance with the procedure recommended by the British Society of Audiology (2018). Pure-tone thresholds were measured at 0.25 kHz, 0.5 kHz, 1 kHz, 2 kHz, 4 kHz and 8 kHz, with thresholds averaged from all frequencies to determine the pure-tone average across both ears. This was to ensure that younger adults had normal hearing, and any age-related differences in multisensory performance were not due to moderate-severe hearing loss in the older adult sample.

The PTA thresholds of younger and older adults are displayed in *Figure 1*. An independent *t*-test revealed that there was a significant difference between age groups on the PTA assessment – older adults (*M*=20.50, *SD*=8.06) had significantly higher PTA thresholds compared to younger adults (*M*=4.25, *SD*=3.28; *t*(62) = 10.56, *p*<.001).

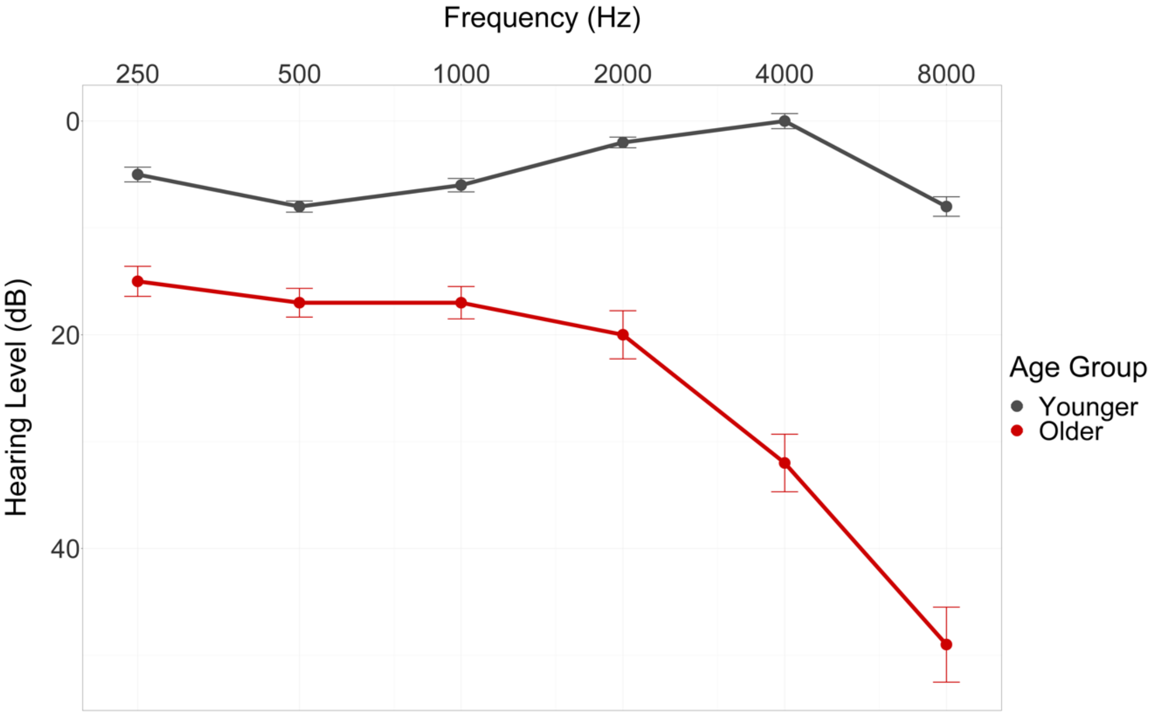


Figure 1. Mean pure-tone audiometry thresholds recorded for each age group at each frequency. Black markers represent data of younger adults, red markers represent the data of older adults. Error bars reflect standard error.

6.4.3. Experimental Design

This study implemented a 2 (Age: Younger vs Older) x 2 (Distractibility Condition: Low vs High) x 3 (TMS Location: Vertex [Cz] vs Parietal [P4] vs Auditory [STG]) mixed design, with Age as the between-subjects factor and Distractibility Condition and TMS Location as the within-subjects factors.

Speech Materials

The speech perception task used in this study was a version of the irrelevant speech paradigm, as implemented by Wostmann et al. (2017). Each trial in the task consisted of audio recordings of a British male speaking the digits 1 to 9. Presentation of the full 9-digit span lasted 9 seconds. These digits served as the task-relevant, to-be-attended target speech (Wostmann et al., 2017).

The task-irrelevant sentences within the paradigm were spectrally degraded, adjusting the acoustic detail of the sentences to manipulate their intelligibility, and therefore their distractibility (i.e. high intelligibility would result in the sentence being highly distracting; low intelligibility would result in the sentence being less distracting; Wostmann & Obleser, 2016; Wostmann et al., 2017). The sentences were degraded using different frequency channels (ch) for noise-vocoding – a higher number of frequency channels results in greater acoustic detail and enhanced intelligibility (Faulkner et al., 2001; Wostmann & Obleser, 2016). As such, the sentences were divided into two vocoding conditions: 1-ch vocoded speech, which was unintelligible therefore easy to ignore (herein referred to as the Low Distractibility condition); and 32-ch vocoded speech, which was more intelligible and therefore more difficult to ignore (herein referred to as the High Distractibility condition). The sentences were based on the

Speed and Capacity of Language Processing Test (SCOLP) sentences (Baddeley et al. 1992). 90 different sentences were utilised, all spoken by the same male voice as the digits that had to be recalled. The task-irrelevant sentence was played immediately after the stimulation, and lasted 1 second. The time period immediately after the target sentence was played, encompassing the delivery of the TMS pulses and the task-irrelevant sentence, was 5 seconds in total.

TMS protocol

Biphasic TMS pulses were generated by a DuoMag XT-100 unit with Wasserman safety limits enabled (Deymed Diagnostic, Hradec Kralove, Czech Republic) and delivered by a 70mm diameter figure-of-8 coil. Pulses were delivered at participants' individual alpha frequency (IAF), which can range between 8Hz-12Hz. In a short pre-test session, participants had their resting brain activity recorded, with their eyes closed, for 2 minutes. Each participant's individual alpha frequency was identified from the EEG data according to an automated resting-state individual alpha frequency estimation routine implemented in MATLAB (Corcoran et al., 2018).

TMS pulses were delivered at an intensity that reflected the average resting motor threshold (rMT) of the hand area of left motor cortex. Previous literature suggests that the average rMT for younger adults is approximately 45% TMS intensity (Gaffney et al., 2021). Since the efficacy of TMS stimulation is dependent on close contact with the scalp, the use of the EEG cap in this study introduced an increase in the coil-to-cortex distance, which would decrease the efficacy of stimulation. Research suggests that for each additional millimetre in coil-to-scalp distance an additional 2.8% or 2.5% of TMS stimulator output is required to elicit the same effect (Stokes et al., 2007; Trillenberg et al., 2012). Since the EEG cap and electrode ring introduces approximately 10mm additional coil-to-cortex distance, stimulator output in this study increased by 25%, to account for the 2.5% increase per mm. As such, participants received stimulation at 70%, which was applied on top of the EEG cap.

Three brain locations across the task were stimulated in a randomised order. These locations were the vertex (identified as the location of the central electrode, Cz), the parietal cortex (identified as the location as the right parietal electrode, P4), and the auditory cortex (consistent with the left superior temporal gyrus [STG] at MNI co-ordinates x = −60, y = −12, z = −6; Kennedy-Higgins et al., 2020). MNI co-ordinates for the auditory cortex were based on the location identified by Kennedy-Higgins et al. (2020); these co-ordinates were mapped onto an average brain model based on the MRI data of 40 adults, with stimulation position facilitated using BrainSight neuronavigation systems (Rogue Research Inc, Canada). As a result, throughout this manuscript, TMS to the parietal cortex will be referred to as the P4 location, TMS to the auditory cortex will be referred to as the STG location, and TMS to the vertex will be referred to as the Cz location. In each location, participants received 5 pulses of TMS delivered at their IAF, before the presentation of the irrelevant sentence.

6.4.4. Procedure.

The behavioural task used in this study is an auditory working memory task based on the irrelevant speech paradigm (Colle & Welsh, 1976; Wostmann et al., 2017). During a trial of the auditory working memory task, participants focussed on a fixation cross, and listened to an audio recording of the digits 1 to 9 spoken in a random order. Participants were asked to remember the order of these 9 digits – this is the attending phase. After this, participants received 5 pulses of TMS set at their individual alpha frequency (IAF), to either the vertex, the parietal cortex or the auditory cortex. A task-irrelevant sentence was then played, consisting of either low distractibility or high distractibility speech – this was the inhibition phase, in which participants were required to hold the digits in memory whilst inhibiting the irrelevant sentence. Finally, in the recall phase, participants were presented with a keypad on the screen containing the numbers 1 to 9; these numbers were presented in a random arrangement after each trial (to prevent participants' motor preparation influencing their behavioural responses; Wostmann et al., 2017). Participants used the mouse to click the digits in the order they were presented in; all digits had to be selected before the next trial could begin.

Participants completed 6 practice trials prior to the commencement of the experiment, two per TMS Location. Participants completed 40 experimental trials in total – 20 trials in the 1-ch, low distractibility condition and 20 trials in the 32-ch, high distractibility condition – for each TMS location. The order of the trials in each Distractibility condition was randomised for each participant. The order in which each brain area was stimulated with pseudo-randomised for each participant. Participants had the opportunity for a break after every 13 trials, with a longer break at the end of each block of 40 trials when TMS location was to be changed. Stimuli were presented using Presentation software (Version 18.0, Neurobehavioural Systems, Inc., Berkeley, CA, www.neurobs.com), with auditory stimuli played binaurally through ER2-insert earphones (Etymotic Research). The procedure for this experiment is displayed in *Figure 2.*

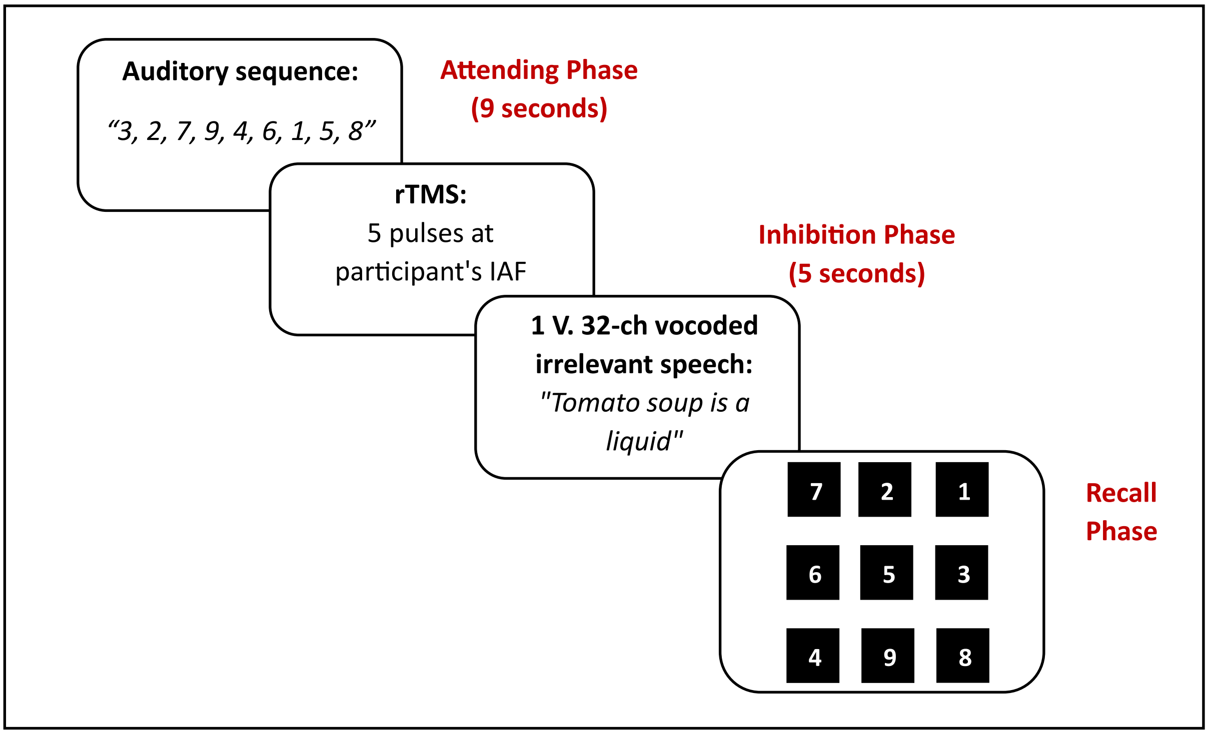


Figure 2. Procedure detailing the steps of the experimental task. Participants were asked to listen to and remember the digits in the attending phase; 5 pulses of TMS were then delivered at each participant's individual alpha frequency (IAF); after this, participants heard a task-irrelevant sentence which was of low distractibility (1-ch) or high distractibility (32-ch). Participants then click on the screen to identify the order in which the 9 digits in the target sentence were spoken.

6.4.5. EEG recording and pre-processing

Continuous EEG data were sampled at 2048Hz from a 32-channel BioSemi Active Two acquisition system (BioSemi V.O.F, Amsterdam, The Netherlands). Electrodes were positioned according to the international 10-20 system, using the average of all electrodes as reference during recording. Data were collected using Presentation software (Version 18.0, Neurobehavioural Systems, Inc., Berkeley, CA) to send EEG triggers time-locked to specific events within the task, and ActiVIEW for collecting and storing EEG data. Processing and EEG analyses were completed offline using the EEGLAB toolbox (Delorme & Makeig, 2004) and MATLAB scripts.

TMS pulse removal. To remove the artifacts that existed within the data as a result of the TMS pulses, the TMS-EEG signal analyser (TESA) package was used in MATLAB (Rogasch et al., 2017; Mutanen et al., 2020). This package identified each of the TMS pulses present in the data file, and removed data 2ms before each pulse and 50ms after each pulse. This missing data was then replaced with average data that occurred between 800ms and 300ms before the first TMS pulse; this interpolation was conducted to replace data from what was the first TMS pulse to what was the fifth TMS pulse in each train (Rogasch et al., 2017; Mutanen et al., 2020).

Pre-processing. After TMS pulse removal, the EEG data were resampled to 256Hz, re-referenced to the average of all electrodes, and a digital low cut-off filter of 0.1Hz and a high cut-off filter of 44Hz was applied. An independent component analysis (ICA) was performed on the data. Artefactual independent components were detected and rejected using the ICFlag function in EEGLAB; components that were identified as being over 80% likely to be heart, muscle or eye artefacts were removed from the dataset (Delorme et al., 2007). The pre-processed EEG data were epoched, beginning 50ms before the presentation of the task-relevant digits, and ending 14 seconds later after the task-irrelevant sentence had ended.

Alpha power extraction. Baseline-corrected alpha power was extracted from the 8-12Hz frequency band at electrodes positioned over the right parietal cortex (P4, P8, PO4; denoting parietal alpha power) and the left auditory cortex (T7, F7, FC5; denoting auditory alpha power). These target brain areas are displayed in *Figure 3.* Alpha power was determined using the power spectral density (PSD) package in EEGLAB. The 'spectopo' function is based upon Welch's method and uses a 256-point Hamming window. This resulted in each participant having 6 parietal alpha power values (one for each Distractibility x TMS Location condition of the task) and 6 auditory alpha power values.

Gamma power extraction. To investigate whether entraining alpha oscillators could also modulate gamma-band activity, baseline-corrected low gamma power was extracted from the 30-44Hz frequency band at electrodes positioned over the right parietal cortex (P4, P8, PO4; denoting parietal gamma power) and the left auditory cortex (T7, F7, FC5; denoting auditory gamma power). Gamma power was determined using the power spectral density (PSD) package in EEGLAB. The 'spectopo' function is based upon Welsch's method and uses a 256-point Hamming window. This resulted in each participant having 6 parietal gamma power values, one for each Distractibility x TMS Location condition of the task, and 6 auditory gamma power values.

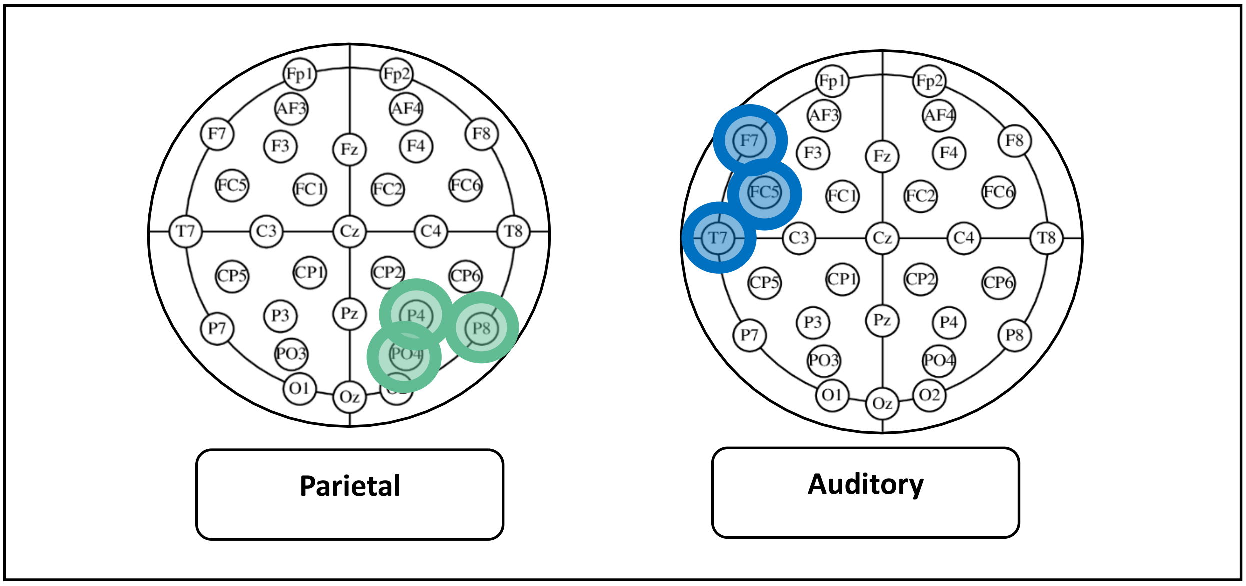


Figure 3. Positions of electrodes used to extract alpha power and gamma power in the target parietal and auditory brain regions.

6.4.6. Statistical Analyses

Behavioural data collected in this study was analysed using mixed ANCOVA models in R studio (version 4.2.1). EEG data collected in this study was analysed using mixed MANCOVA models in SPSS (IBM SPSS Statistics for Windows, Version 28.0. Armonk, New York). Pure-tone audiometry was included as a covariate in each statistical model to control for differences in hearing acuity. An alpha value of p=.05 was used as the threshold for significance.

Behavioural Data Analysis

Behavioural data represented the proportion of digits recalled in the correct position in each TMS location and Distractibility condition, measuring participants' accuracy throughout the task. That is, if a digit was recalled at the position in which it was presented, this was considered "correct", and if it was recalled in any other position, this was "incorrect" (Wostmann et al., 2017). The mean proportion correct was calculated by averaging across trials for each condition. Behavioural data was analysed using a 2 (Age: Younger vs Older) x 2 (Distractibility Condition: Low vs High) x 3 (TMS Location: Vertex [Cz] vs Parietal [P4] vs Auditory [STG]) mixed ANCOVA in RStudio (version 4.2.1). Pure-tone audiometry thresholds were included as a covariate to account for the impact that any differences in hearing ability between younger and older adults would have on the results.

EEG Data Analysis

EEG data consisted of baseline-corrected alpha power recorded during the attending and maintenance phases of the task, for each Distractibility condition and TMS location. There were two dependent variables of interest within the EEG data – the first dependent variable was baseline-corrected alpha power recorded over the auditory cortex, whilst the second dependent variable was baseline-corrected alpha power recorded over the parietal cortex. Despite the fact that alpha power was also recorded over Cz, there were no specific hypotheses for this location, so it was not subject to analyses as an outcome variable. Due to the fact that there were two dependent variables within the EEG data, it was decided to analyse parietal and auditory alpha power using a 2 (Age: Younger vs Older) x 2 (Distractibility Condition: Low vs High) vs 3 (TMS Location: Vertex [Cz] vs Parietal [P4] vs Auditory [STG]) mixed MANCOVA (Multivariate Analysis of Covariance). Pure-tone audiometry thresholds were included as a covariate to account for the impact that any differences in hearing ability between younger and older adults would have on the results. Means and standard errors reported in the main body of the text represent the estimated marginal means from the mixed MANCOVA (denoted as *M* and *SE*); estimated marginal means are adjusted from the descriptive statistics to account for PTA thresholds as a covariate. These estimated marginal means were used in the statistical analyses to evaluate significance between groups or conditions through pairwise comparisons. For completeness, descriptive statistic means which may differ from estimated marginal means (i.e. the raw means calculated without the influence of PTA threshold as a covariate) are displayed on graphs where relevant (denoted as M_{Raw} and SE_{Raw}). Power values which were deemed extreme due to any excessive noise during recording were removed and replaced with the age group mean value in each condition. Any further outliers which were +/- 3 standard deviations from the age group mean were also removed and replaced with the age group mean in each condition. This did not exceed 10% of the dataset.

Exploratory analyses – gamma power. To explore the impact of entraining alpha oscillators on the relationship between alpha power and gamma power in parietal and auditory regions, and how this may change with healthy ageing, Spearman's rank-order correlations were conducted. Alpha powers were collapsed across distractibility conditions, to produce a mean parietal alpha power, mean parietal gamma power, mean auditory alpha power and mean auditory gamma power, for each participant after each TMS location was stimulated. The data file was split by age, and correlations were conducted between parietal alpha/gamma power after alpha-TMS to Cz, P4 and STG locations, and between auditory alpha/gamma power after alpha-TMS to Cz, P4 and STG locations.

6.4.7. Deviations from pre-registration

Whilst the data in the current study are not normally distributed, previous research indicates that the *F*-test in ANCOVA models is robust to this (Schmidt & Finan, 2018), particularly due to the relatively large sample size and equal numbers within each group. Furthermore, given that younger and older adults display similar distributions, we believe that transforming the data to correct for such assumptions would result in a model less reflective of how age-related changes in auditory working memory manifest. As such, data in the MANCOVA model were not transformed, however Greenhouse Geisser adjusted statistics are used where appropriate. As further exploratory analyses, correlations were conducted between alpha power and gamma power in parietal and auditory regions, to measure how entraining alpha oscillators associated with gamma power. Given that Pearson's correlations are less robust to non-normal distributions (Mukaka, 2012), Spearman's rank-order correlations were used for these alpha-gamma coupling analyses. Alpha power within each phase of the experiment (attending, maintenance and recall) was not analysed to constrain type I error and enable a closer replication of the analyses of Wostmann et al. (2017), who measured alpha power in younger adults across the total time period encompassing digit presentation and inhibition of distracting speech in the irrelevant speech paradigm.

6.5. Results

6.5.1. Behavioural data – proportion of digits recalled in the correct order

The proportion of digits recalled in the correct position, for each position within each Distractibility condition and TMS location, is displayed in *Figure 4*. The mean proportion of digits correctly recalled, in total for each condition, is displayed in *Figure 5*.

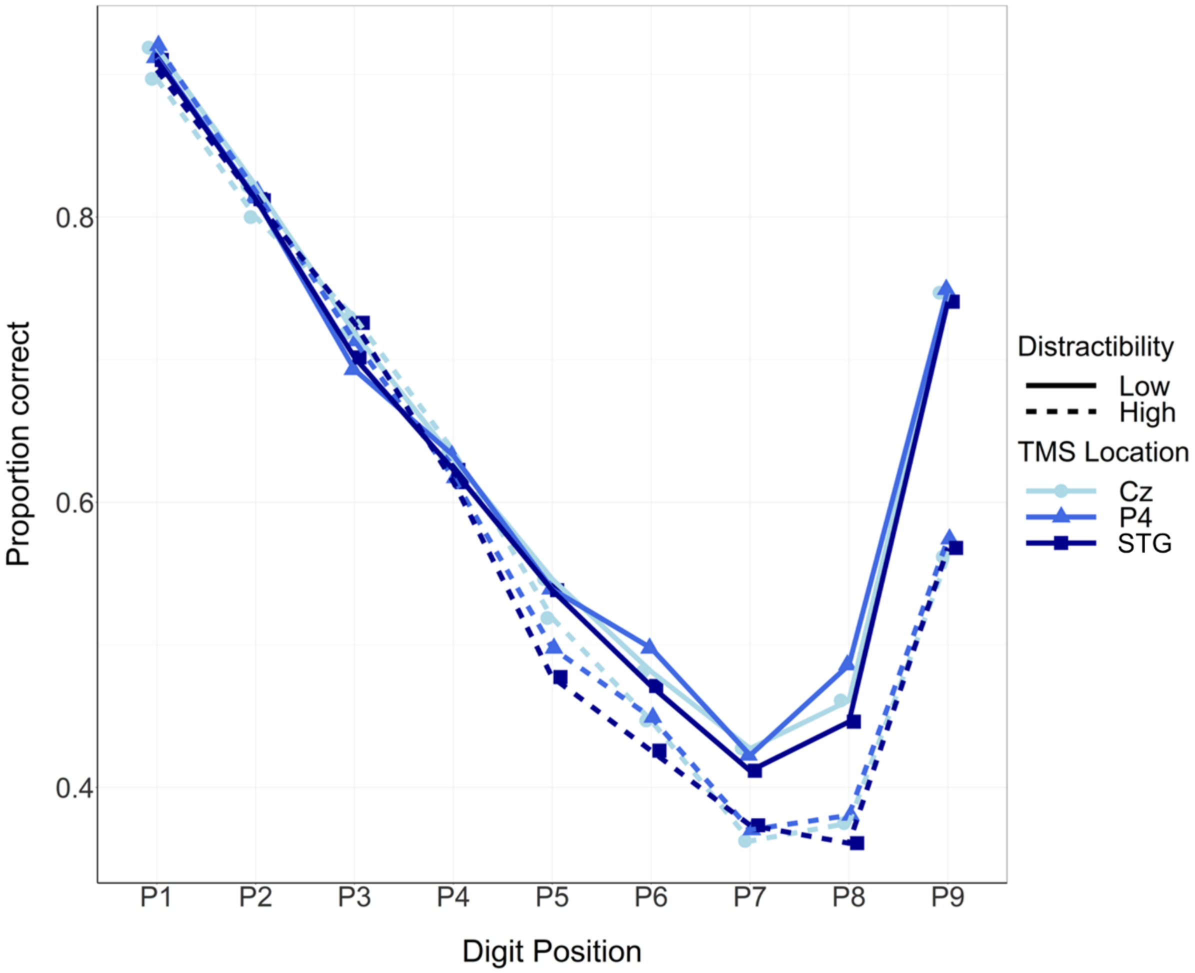


Figure 4. Proportion of digits recalled in the correct position, across all ages, for each of the 9 positions within the speech perception task. Solid line displays data from Low Distractibility conditions, dashed line displays data from High Distractibility conditions. Light blue line displays proportion correct after Cz was stimulated; medium blue line displays proportion correct after P4 was stimulated; dark blue line shows proportion correct after STG was stimulated.

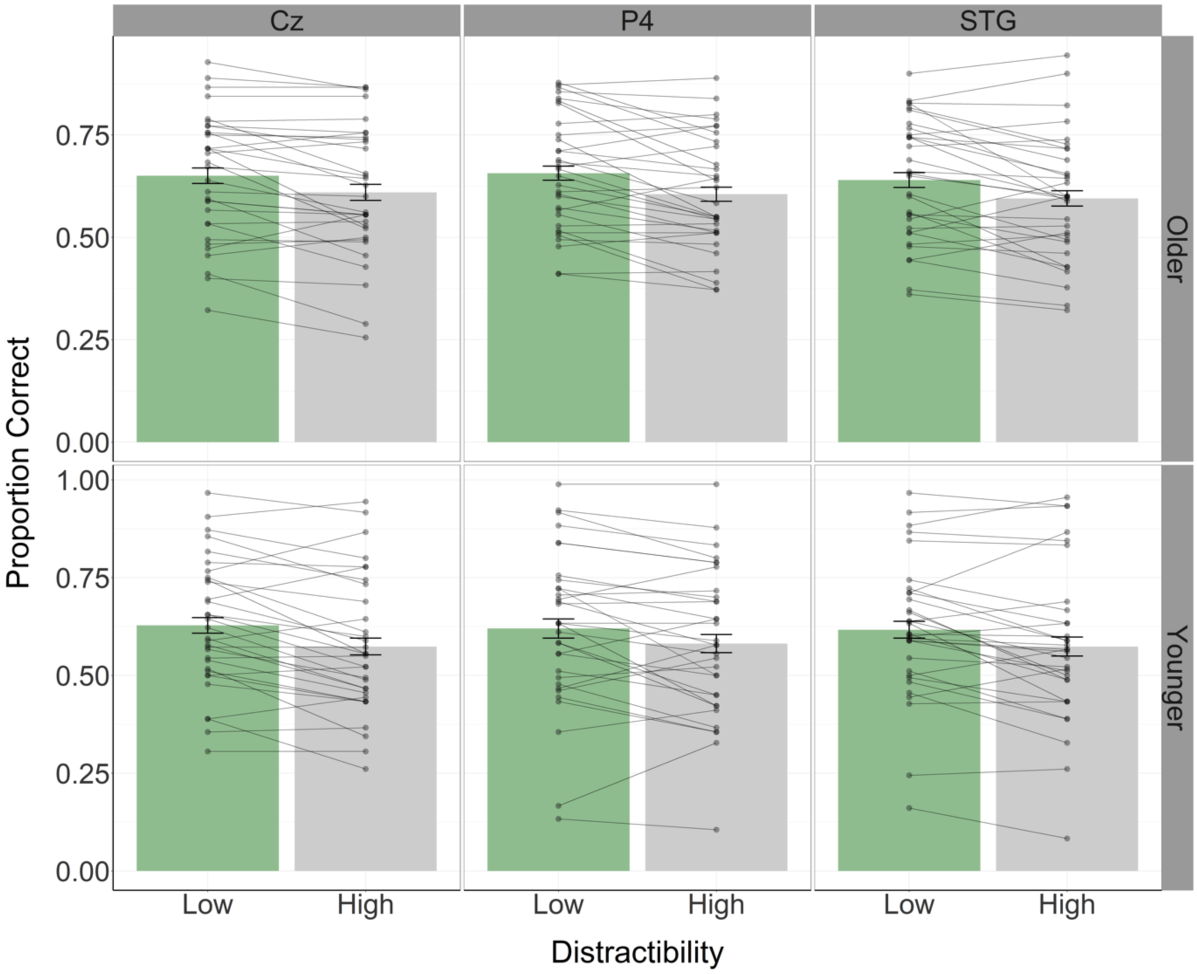


Figure 5. Mean proportion of digits recalled in the correct order within each Distractibility and TMS condition. Older adult data displayed in the top row, younger adult data displayed in the bottom row. Each data point displays the mean proportion for each participant in that condition. Participants' data points in Low vs High Distractibility conditions are linked by lines.

Behavioural data – the proportion of digits recalled in the correct order – were analysed using a 2 (Age: Younger vs Older) x 2 (Distractibility: Low vs High) x 3 (TMS location: Vertex vs Parietal vs Auditory) mixed ANCOVA, with pure-tone audiometry thresholds included as a covariate. The mixed ANCOVA revealed no significant main effect of Age [*F*(1,61)=0.849, *p*=.361] or TMS location [*F*(2,122)=0.621, *p*=0.539]. There were also no significant interactions between Age and Distractibility [*F*(1,61)=0.155, *p*=.695], between Age and TMS Location [*F*(2,122)=0.012, *p*=0.988], between Distractibility and TMS Location [*F*(2,122)=0.043, *p*=.958), and no significant 3 way interaction between Age, Distractibility and TMS Location [*F*(2,122)=1.63, *p*=.200]. However, there was a significant main effect of Distractibility on the proportion of digits recalled in the correct order [*F*(1,61)=44.63, *p*<.001, ηp^2=0.42]. Overall, a greater proportion of digits were recalled in the correct order in the Low Distractibility conditions (*M*=0.64, *SE*=0.16) compared to the High Distractibility conditions (*M*=0.59, *SE*=0.17). This main effect is displayed graphically in *Figure 6*.

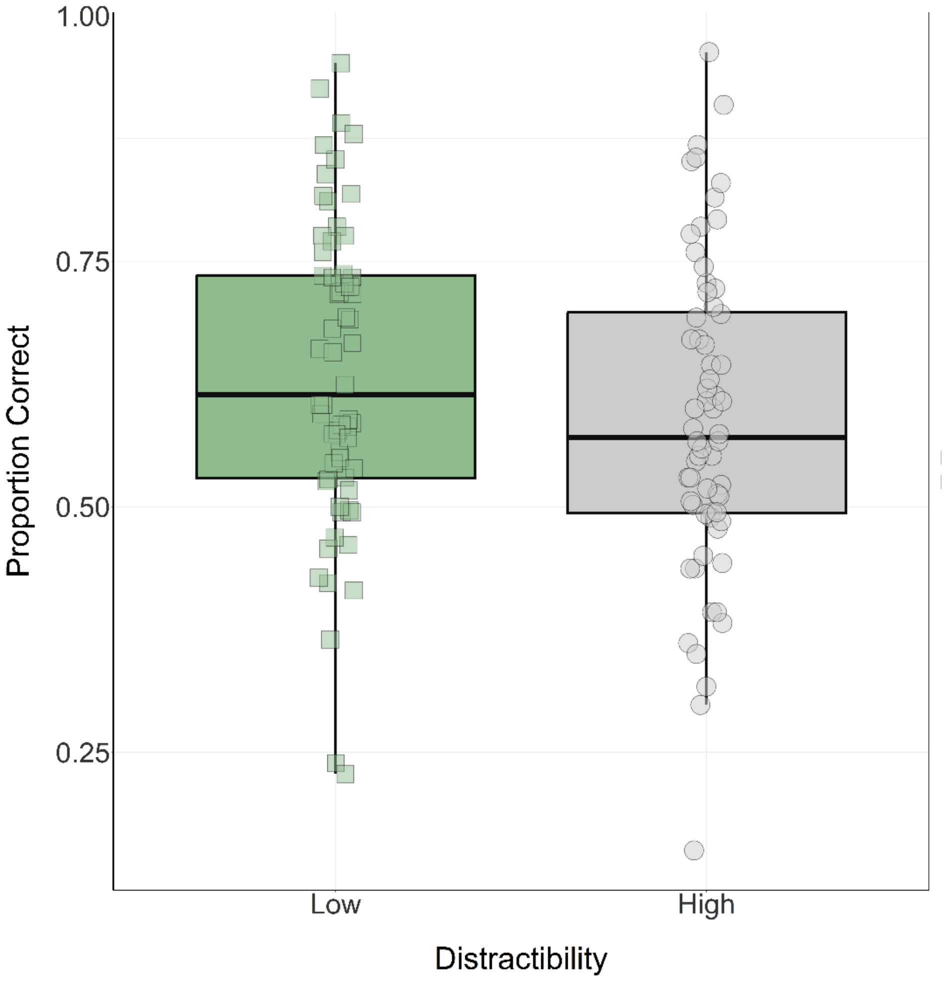


Figure 6. Proportion of digits recalled in the correct position in the Low vs High Distractibility conditions, collapsed by Age and TMS location.

6.5.2. EEG data – Alpha power

Alpha power recorded over the parietal cortex and the auditory cortex were analysed using a 2 (Age: Younger vs Older) x 2 (Distractibility Condition: Low vs High) x 3 (TMS Location: Cz x P4 x STG) mixed MANCOVA, with pure-tone audiometry thresholds as a covariate.

Effect of Age

Using the Wilks' criterion, the mixed MANCOVA revealed that parietal alpha power and auditory alpha power were significantly different across age groups (Wilk's Lambda = 0.765, *F*(2,60)=9.23, *p*<.001, ηp^2=0.24). With regards to parietal alpha power, there was a significant main effect of Age [*F*(1,61)=18.73, *p*<.001, ηp^2=0.24]. Older adults had greater parietal alpha power (*M*=7.33, *SE*=0.79) compared to younger adults (*M*=1.31, *SE*=0.79; mean difference=-6.02, *SE*=1.39, *p*<.001). In addition, there was a significant main effect of Age on auditory alpha power [*F*(1,61)=4.30, *p*=.042, ηp^2=0.07] – older adults had greater auditory alpha power (*M*=4.90, *SE*=0.63) compared to younger adults (*M*=2.58*, SE*=0.63; mean difference = 2.31, *SE*=1.12, *p*=.042). The main effect of age for both parietal alpha power and auditory alpha power is displayed in *Figure 7*.

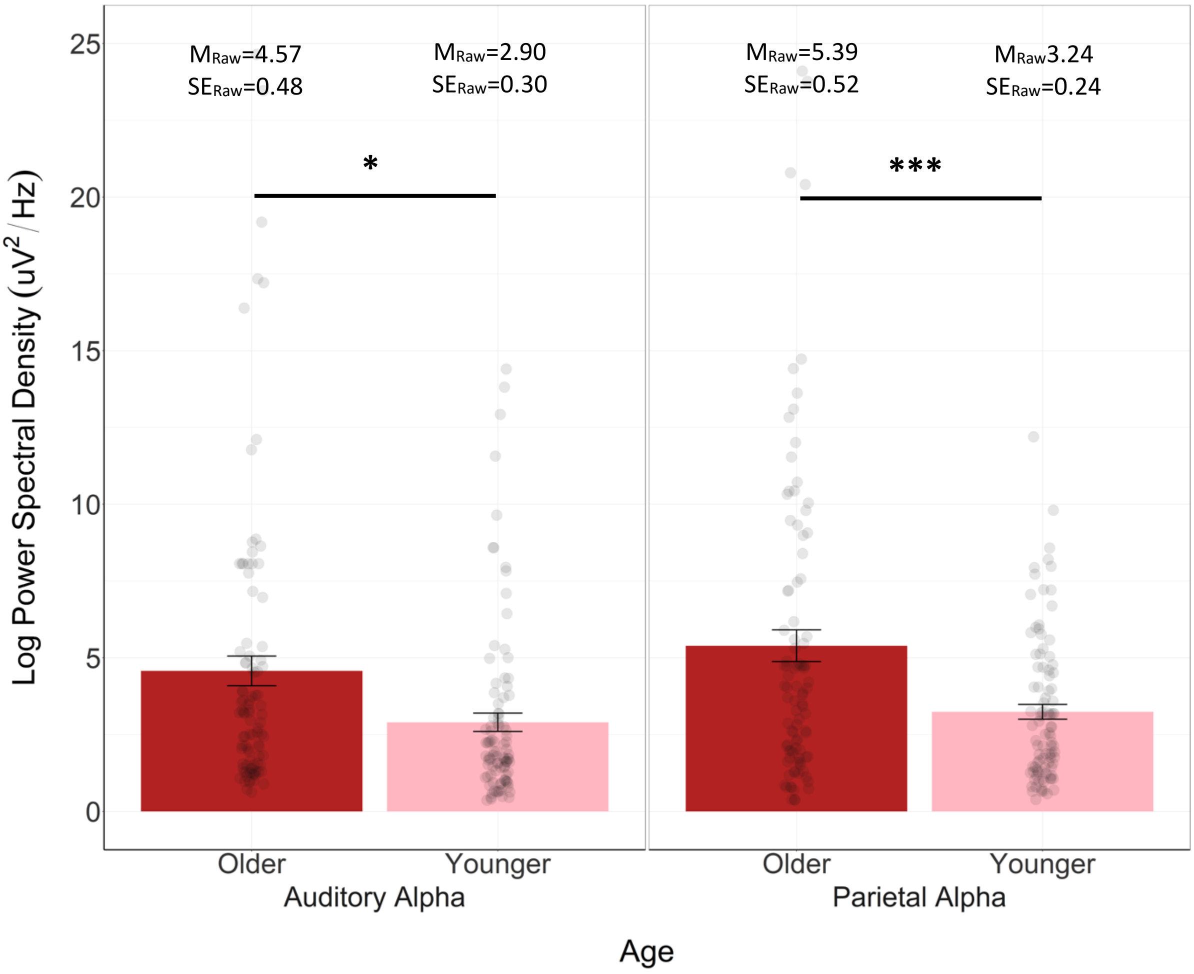


Figure 7. Mean alpha power recorded over auditory and parietal brain regions, collapsed across Distractibility conditions and TMS locations, for younger and older adults. Each point represents the alpha power of each participant across the Distractibility conditions and TMS locations. *** represents significance at p=<.001, ** represents significance at p=<.01, * represents significance at p=<.05

Effect of TMS Location

Using the Wilks' criterion, the mixed MANCOVA revealed that parietal alpha power and auditory alpha power were significantly different across each TMS Location (Wilk's Lambda = .839, *F*(4,242) = 5.60, *p*=<.001, ηp^2=.085). The mixed MANCOVA also indicated that Mauchly's test of sphericity was violated for TMS Location in parietal alpha power (χ^2 =102.26, *p*<.001) and auditory alpha power (χ^2 =44.37, *p*<.001), therefore Greenhouse-Geisser adjusted p-values are reported. With regards to parietal alpha power, there was a significant difference across TMS Locations [*F*(1.31,80.12)=5.48, *p*=.009, ηp^2=.092]. Parietal alpha power was greater after TMS to P4 (*M*=5.62, *SE*=64) than to Cz (*M*=3.59, SE=0.33; mean difference = 2.03, *SE*=0.52, *p*<.001) and to STG (*M*=3.75, *SE*=0.33; mean difference = 1.87, *SE*=0.55, *p*=.004). With regards to auditory alpha power, there was also a significant difference across TMS locations [*F*(1.10,67.10)=5.48, *p*=.020, ηp^2=0.082]. Auditory alpha power was greater after TMS to STG (*M*=6.53, *SE*=0.68) than to Cz (*M*=2.20, *SE*=.17; mean difference = 4.34, *SE*=0.65, *p*<.001) and to P4 (*M*=2.49, *SE*=0.24; mean difference =4.05, *SE*=0.62, *p*<.001). This indicates that in both parietal and auditory cortices, TMS was effective in entraining alpha oscillators to enhance alpha power. The main effect of TMS location for both parietal alpha power and auditory alpha power is displayed in *Figure 8*.

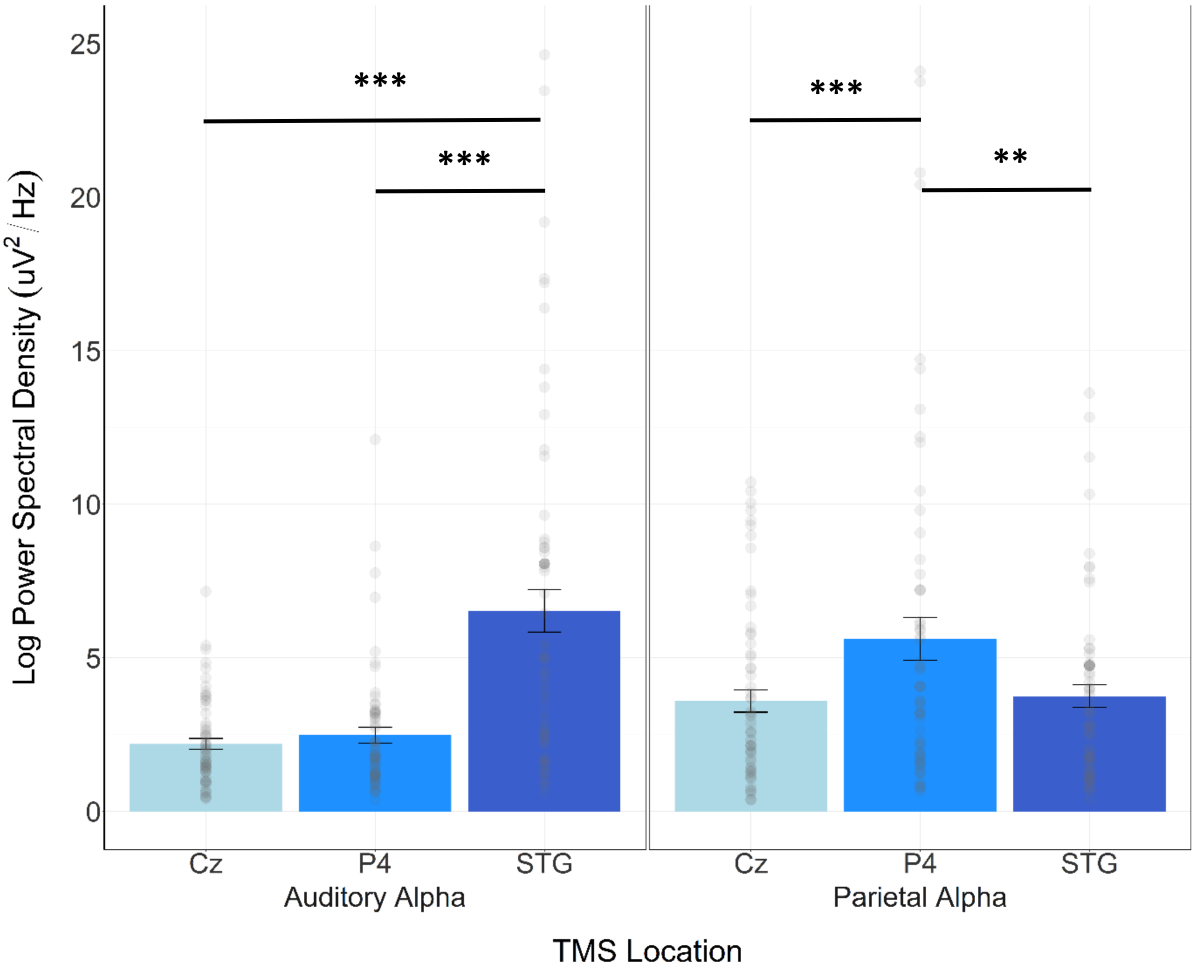


Figure 8. Mean alpha power recorded over auditory and parietal brain regions, collapsed across Distractibility conditions and age groups, for each TMS Location. Each point represents the alpha power recorded by each participant. *** represents significance at p=<.001, ** represents significance at p=<.01, * represents significance at p=<.05

The mixed MANCOVA revealed no significant main effect of Distractibility on parietal and auditory alpha power [Wilk's Lambda = .977, *F*(2,60) = 0.70, *p*=.502, ηp^2=.02].

Interaction between Location and Distractibility

The MANCOVA revealed that there was a significant interaction between TMS Location and Distractibility condition on parietal alpha power and auditory alpha power (Wilk's Lambda = .902, *F*(4,242)=3.19, *p*=.014, ηp^2=0.050).

With regards to parietal alpha power, there was a significant interaction between TMS Locations and Distractibility conditions [*F*(2, 122)= 6.52, *p*=.002, ηp^2=.097]; however, this two-way interaction was not significant in auditory alpha power [*F*(2, 122)=0.10, *p*=.904, ηp^2=.002]. Pairwise comparisons arising from this two-way interaction within the parietal alpha power data were analysed to assess how parietal alpha activity differs between TMS locations and Distractibility conditions.

Pairwise comparisons revealed that after alpha-TMS to P4, a greater parietal alpha was recorded in the High Distractibility condition (*M*=6.16, *SE*=0.76) compared to the Low Distractibility condition (*M*=5.08, *SE*=0.57; mean difference = 1.09, *p*=.007). In contrast, difference in parietal alpha power in Low vs High Distractibility conditions was not significant after TMS to Cz (*p*=.097) or TMS to STG (*p*=.082). This significant interaction is displayed in *Figure 9*. The significant difference in parietal alpha power in Low and High distractibility conditions when P4 was stimulated may be indicative of the role of parietal alpha power in inhibitory control.

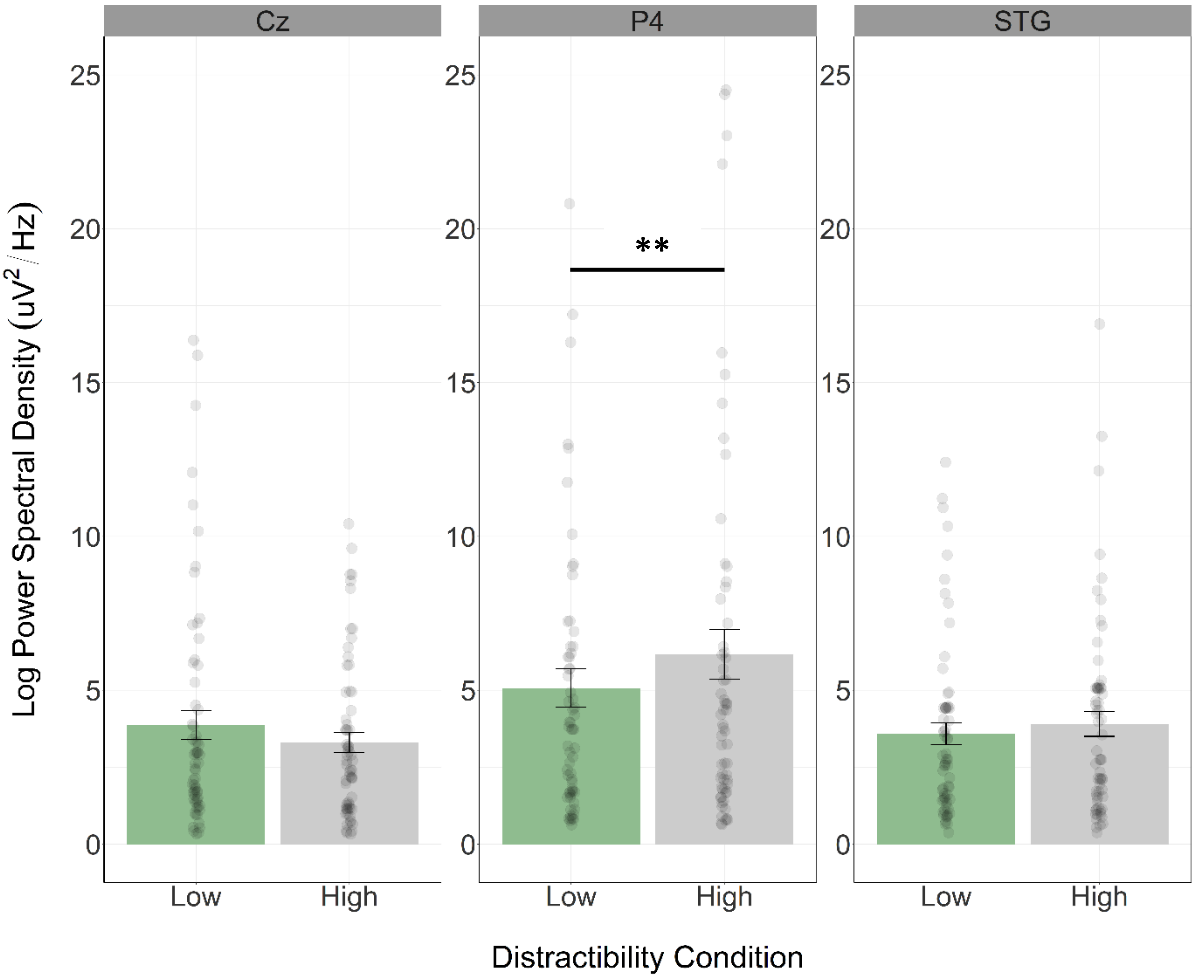


Figure 9. Graph to illustrate the significant interaction between TMS Location and Distractibility condition on parietal alpha power. Each point represents the parietal alpha power recorded by each participant across conditions. *** represents significance at p=<.001, ** represents significance at p=<.01, * represents significance at p=<.05

Interaction between Age, Location and Distractibility.

The MANCOVA also revealed that there was a significant three way interaction between Age, TMS Location and Distractibility condition on parietal alpha power and auditory alpha power (Wilk's Lambda = 0.898, *F*(4,242)=3.35, *p*=.011, ηp^2=0.052). With regards to parietal alpha power, there was a significant interaction between Age, TMS Location and Distractibility [*F*(2,122)=5.21, *p*=.007, ηp^2=0.079]; however, with regards to auditory alpha power, there was no significant interaction between Age, TMS Location and Distractibility [*F*(2, 122)=1.59, *p*=.209, ηp^2=0.025]. To analyse the significant three-way interaction present in parietal alpha data, the data file was split by age group, and two separate 2 (Distractibility: Low vs High) x 3 (TMS Location: Cz vs P4 vs STG) repeated-measures ANCOVAs were conducted on the data.

The repeated-measures ANCOVA of parietal alpha power in older adults revealed a significant interaction between Location and Distractibility [*F*(2, 60) = 3.87, *p*=.026, ηp^2 = 0.11]. Pairwise comparisons revealed that in P4 TMS locations, parietal alpha power was higher in High distractibility conditions (*M*=7.97, *SE*=1.45) compared to Low distractibility conditions (*M*=6.42, *SE*=1.13; mean difference = 1.55, p=.036). In contrast, in Cz TMS locations, there was no significant difference in parietal alpha power between Low and High distractibility conditions (*p*=.103). In addition, in STG TMS locations, there was no difference in parietal alpha power between Low and High distractibility conditions (*p*=.055). The model also revealed that for older adults, there was no significant main effect of Location [*F*(2, 60)=2.95, *p*=.060, ηp^2 =0.09] or Distractibility [*F*(1,30)= 0.32, *p*=.574, ηp^2 = 0.01].

In contrast to the data of older adults, the 2 (Distractibility: Low vs High) x 3 (TMS Location: Cz s P4 vs STG) repeated-measures ANCOVA on the parietal alpha power of younger adults did not reveal a significant interaction between Location and Distractibility [*F*(2,60)=2.16, *p*=.124, ηp^2 =0.07]. There were also no significant main effects of Location [*F*(2,60)=2.89, *p*=.063, ηp^2 = 0.06] or Distractibility [*F*(1,30)=0.26, *p*=.617, ηp^2 = 0.01] on parietal alpha power in younger adults. The alpha powers of younger and older adults, in each TMS Location and Distractibility condition, are displayed in *Figure 10*.

Taken together, the significant difference in parietal alpha power in Low and High distractibility conditions when P4 was stimulated may be indicative of the role of parietal alpha power in inhibitory control for older adults. This interaction was not significant in younger adults; the implications of this, for understanding of how alpha power may reflect age-related changes in auditory working memory, are explored in the discussion section.

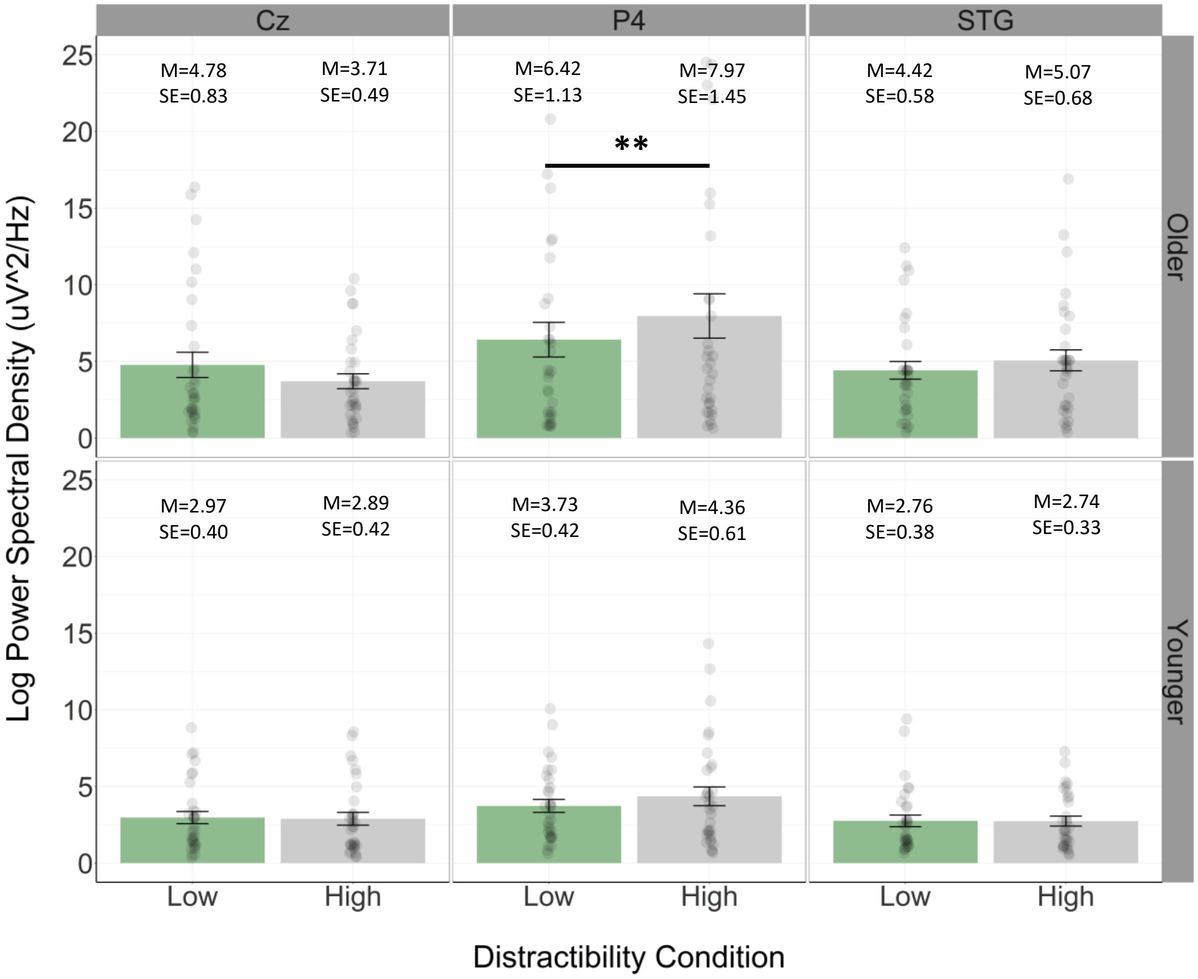


Figure 10. Three-way interaction between Age, Distractibility and TMS location in parietal alpha power. Parietal alpha power was greater in High distractibility conditions compared to Low distractibility conditions when P4 was stimulated. Younger adults showed no significant differences across TMS locations in each distractibility condition. *** represents significance at p=<.001, ** represents significance at p=<.01, * represents significance at p=<.05

Exploratory analyses: alpha-gamma coupling

To analyse power-power coupling between alpha and gamma in younger and older adults in each TMS Location, Spearman's rank-order correlational analyses were conducted (Abubaker et al., 2021). Given that our exploratory hypotheses centred around age-related changes in alpha-gamma coupling, alpha power and gamma power were collapsed across distractibility conditions to produce a mean alpha power and a mean gamma power for each participant in each TMS location condition. The data file was split by age and correlations were conducted separately for each age group.

Alpha-gamma coupling in older adults. The first set of Spearman's rank-order correlations analysed the relationship between parietal alpha power and parietal gamma power in older adults. In conditions where P4 was stimulated, there was no significant relationship between parietal alpha power and parietal gamma power [*r*(30)=0.349, *p*=.051]. There was also no significant relationship between parietal alpha power and parietal gamma power when Cz was stimulated [*r*(30)=0.147, *p*=.423] or when STG was stimulated [*r*(30)=0.249, *p*=.169].

The second set of correlations analysed the relationship between auditory alpha power and auditory gamma power in older adults. There were no significant correlations between auditory alpha power and auditory gamma power when STG was stimulated [*r*(30)=0.068, *p*=.713], when Cz was stimulated [*r*(30)=0.290, *p*=.108], or when P4 was stimulated [*r*(30)=0.005, *p*=.971].

Alpha-gamma coupling in younger adults. The third set of Spearman's rank-order correlations analysed the relationship between parietal alpha power and parietal gamma power in younger adults. There were no significant correlations between parietal alpha power and parietal gamma in conditions where P4 was stimulated [*r*(30)=0.165, *p*=.367], where Cz was stimulated [*r*(30)=0.306, *p*=.089], or where STG was stimulated [*r*(30)=0.188, *p*=.304]

The final set of correlations analysed the relationship between auditory alpha power and auditory gamma power in younger adults. There was a significant moderate positive correlation between auditory alpha power and auditory gamma power in conditions where STG was stimulated [*r*(30)=0.433, *p*=.013]. There was also a significant moderate positive correlation between auditory alpha power and auditory gamma power in conditions where P4 was stimulated [*r*(30)=0.434, *p*=.013] and where Cz was stimulated [*r*(30)=0.461, *p*=.008]. These significant relationships suggest that younger adults may exhibit alpha-gamma coupling in auditory cortex during speech perception in which target speech must be attended to and irrelevant speech must be inhibited. Due to the fact that there was a significant relationship between auditory alpha power and auditory gamma power when Cz was stimulated, these observations are not a specific effect of TMS. The non-significant relationships in the older adult data may indicate that older adults exhibit weaker alpha-gamma coupling compared to younger adults, in support of hypothesis 4.

6.6. Discussion

The aim of this study was to investigate whether TMS can entrain alpha oscillations to facilitate auditory working memory in younger and older adults. Whilst our behavioural data support previous research indicating that background speech high in acoustic detail is more difficult to inhibit, there was no behavioural difference between younger and older adults. However, when analysing parietal and auditory alpha power, these age-related changes in auditory working memory become evident – parietal and auditory alpha power were higher in older adults compared to younger adults, which could have important implications for our understanding of the speech perception mechanisms relied upon by our ageing population. Furthermore, in the most distracting listening conditions, TMS to the parietal cortex appeared to enhance parietal alpha power, which may indicate the role of parietal alpha activity in the inhibition of distracting, task-irrelevant information. Crucially, this study provides support for the utility of non-invasive brain stimulation techniques like TMS in modulating neural oscillations, in that entraining alpha oscillators in parietal and auditory cortices successfully enhanced alpha power in each brain region. To investigate how modulating alpha activity may exert a top-down influence on bottom-up sensory processing, we also analysed how alpha activity may associate with gamma power; we found that younger adults exhibited significant positive relationships between auditory alpha power and auditory gamma power across all TMS locations whilst older adults exhibited non-significant relationships. Taken together, these findings could cast light on the interplay between bottom-up and top-down mechanisms during speech perception, and how these may change as a function of healthy ageing.

Across age groups, speech perception appeared to be more challenging in highly distracting listening environments.

Through analysing the percentage of digits recalled in the correct order, our behavioural data analyses revealed that both younger and older adults produced a weaker performance in the highly distracting, 32-channel vocoded conditions compared to the less distracting, 1-channel vocoded conditions. This is in line with previous research which implemented noise-vocoded speech perception tasks and found that the greater the acoustic detail of the task-irrelevant, to-be-ignored speech, the more distracting and detrimental it is to the maintenance of relevant target-speech (Wostmann et al., 2017; Ellermeier et al., 2015; Wostmann & Obleser, 2016). If the background speech is clear and rich in acoustic detail, it is naturally more difficult to ignore compared to background speech that may be of poor quality or lower in dB level (however, see research by Scholz and colleagues, 2023, which suggests that whispered speech, despite being lower in volume, can be more distracting than loud speech; this may be due to the greater listening effort required to process the meaning of whispered speech). In sum, highly distracting background speech can detract from the cognitive resources required to process target speech (Wostmann et al., 2017), resulting in a less accurate speech perception performance in lab environments and weaker/more difficult social communication in everyday life settings.

Despite the importance of this behavioural finding in contributing to our understanding of speech perception in adverse listening environments, it was not reflected in our neural data – there was no significant main effect of Distractibility condition on parietal or auditory alpha power. However, previous studies that have also implemented the irrelevant speech paradigm have not always found complementary results between increased alpha power and increased inhibition of distracting sensory information. This may be due to the fact that, unlike the majority of speech-in-noise studies in which the Distractibility manipulation is applied to the task-relevant speech, the irrelevant speech paradigm deviates from this, manipulating the acoustic detail of the task-irrelevant background noise (Wostmann et al., 2017). Wostmann et al. (2017) postulated that, due to the irrelevant speech paradigm producing behavioural results that pertained to the task-relevant speech (attended digits), and neural results that pertained to both the task-relevant and task-irrelevant speech (attended digits plus inhibited distracting sentences), this brain-behaviour relationship is less direct compared to studies that manipulate the acoustic detail of target speech (producing neural and behavioural data that both pertain to the attended stimulus). Nevertheless, investigating the functional role of entraining alpha oscillations on auditory working memory, in each of these different kinds of paradigms, is key in building a comprehensive understanding of how fluctuations in alpha activity in different brain regions coordinate to support speech perception.

TMS is an effective technique to entrain alpha oscillators in parietal and auditory cortices.

The significant main effect of TMS Location in our EEG analyses supported neural hypotheses one and two. rTMS, set at a participant's individual alpha frequency, was able to significantly increase parietal alpha power when the parietal cortex was stimulated, and significantly increase auditory alpha power when the auditory cortex was stimulated. Historically, the impact of TMS on cortical activity has been inferred through peripheral measurements (e.g. stimulating the motor cortex and recording a motor-evoked potential; Maeda et al., 2000; Pascual-Leone et al., 1994). Through pairing alpha-TMS with concurrent EEG, we are able to record direct cortical responses to stimulation and uncover more about the mechanisms by which alpha-TMS can entrain alpha oscillators in different brain regions. Our neural findings are in line with previous research suggesting that rTMS can result in entrainment of alpha oscillations through the reproduction of naturally-occurring brain rhythms (Thut et al., 2011). Studies like this, which indicate possible mechanisms by which TMS can act upon neural oscillations, can contribute to future research paradigms, not only to improve our understanding of how different neural oscillations may coordinate with each other, but also to measure their functional role in perception and cognition (Thut et al., 2011).

Due to the fact that TMS Location was a non-significant main effect in our behavioural analyses, it is difficult to determine the functional relevance of TMS-induced alpha entrainment in auditory and parietal brain regions. For example, if alpha-TMS can entrain parietal alpha oscillators, this should be an effective protocol to improve a participant's ability to suppress task-irrelevant, distracting information, due to the postulated role of the parietal cortex in inhibition (Thut et al., 2011). As such, perhaps the irrelevant speech paradigm implemented in the current study was not sensitive enough to detect behavioural differences arising from increasing auditory and parietal alpha power. It is likely that an experimental paradigm in which attentional and inhibitory control is even more challenging, such as a task that contains irrelevant speech that is semantically similar to the relevant speech, could uncover the benefits that alpha-TMS to auditory and parietal brain regions could have on behavioural performance, and how this may change as a function of healthy ageing (Bell et al., 2008; Diaz et al., 2019; Tun et al., 2002; Murphy et al., 2018).

Older adults exhibited increased alpha activity compared to younger adults.

Our MANCOVA analyses on EEG data collected in this study also revealed a significant main effect of Age – older adults produced a greater parietal alpha power and auditory alpha power compared to younger adults. This is in contrast to previous research which indicates that reduced parietal alpha power in older adults may be an underlying neural correlate of their weaker inhibitory abilities (Wostmann et al., 2015). However, the findings of the current study may reflect the increased listening effort required by older adults to perceive speech in adverse listening conditions. With increasing age, speech perception tends to become more challenging; in part, this is due to age-related hearing loss in the peripheral auditory system (Slade et al., 2020; Shneider et al., 1997), however it is also a result of age-related deteriorations in the ability to attend to and remember relevant speech and inhibit distracting background noise form external speakers (Pichora-Fuller et al., 1995; Dey & Sommers, 2015; Borghini et al., 2018; Gazzaley et al., 2008). To compensate for such deficits, older adults are believed to engage wider cortical networks during speech perception compared to younger adults (Wong et al., 2009; Frtusova & Phillips, 2016), recruiting an increased amount of cognitive resources in order to disambiguate the speech signal, hold the words in memory, and inhibit distracting information (Peelle et al., 2010; Getzmann et al., 2015).

This is supported by theories such as the compensation-related utilization of neural circuits hypothesis (CRUNCH; Reuter-Lorenz & Lustig, 2005). According to CRUNCH, to produce a behavioural performance similar to that of younger adults, older adults are required to recruit increased neural resources to compensate for age-related processing inefficiencies. This compensatory mechanism is effective when the task is relatively straightforward, however when task difficulty increases, a 'resource ceiling' is reached in older adults, leading to drop-offs in both motivation and performance (Reuter-Lorenz & Cappell, 2008). Older adults in the current study may have compensated for their age-related declines in the bottom-up and top-down mechanisms involved in speech perception by recruiting greater cortical networks, resulting in increased parietal and auditory alpha power, and preserving auditory working memory to produce a behavioural performance that was similar to younger adults (Peelle et al., 2010; Getzmann et al., 2015).

As discussed earlier, the research into whether increases or decreases in auditory alpha power reflect increased attention to target speech is mixed; the current study supports the findings of Obleser et al. (2012) and Dijk et al. (2010), who observed increases in auditory alpha power during challenging auditory tasks and memory retention tasks. More research is needed into the age-related changes in auditory alpha power to determine how fluctuations in alpha activity can impact the facilitation of attention towards target speech. With regards to the parietal cortex, there may be an element of motivation behind the increased parietal alpha power in older adults compared to younger adults – in general, older adults who volunteer to participate in research are found to be more motivated to perform well on cognitive tasks (Frank et al., 2015; Seli et al., 2017; Ryan & Campbell, 2021). That is, if older adults were more invested in producing the most accurate digit recall performance as possible, they may have been allocating more cognitive resources to inhibiting the irrelevant speech – more so than younger adults. Younger adults may not have been as motivated to succeed in the task, or may have found it easier to retain the target digits and inhibit the irrelevant sentence (see Ryan & Campbell, 2021, for a detailed review on the impact that age-related differences in motivation can have on performance in neurocognitive tasks). Taken together, and in line with the CRUNCH framework, increased parietal alpha power and increased auditory alpha power in older adults may reflect the increased recruitment of cognitive resources required to inhibit the irrelevant speech and facilitate attention to the relevant digits, respectively, to preserve behavioural performance in the speech perception task.

Parietal alpha power was higher in the most distracting listening conditions when P4 was stimulated.

When analysing the significant two-way interaction between TMS Location and Distractibility Condition, the mixed MANCOVA revealed that when the parietal cortex was stimulated, parietal alpha power was greater in High distractibility conditions compared to Low distractibility conditions. In contrast, when Cz or STG were stimulated, parietal alpha power displayed no significant difference across distractibility conditions. Crucially, this finding not only provides support for the role of parietal alpha activity in the inhibition of distracting, irrelevant sensory information, but is also a further indication that TMS, set at a participant's individual alpha frequency, is effective in entraining alpha oscillators in the parietal cortex during adverse listening conditions.

This finding may support the side of the argument suggesting that alpha activity may drive speech perception performance via domain-general alpha oscillators – parietal alpha power was enhanced after TMS to P4 in the most distracting listening conditions, whereas auditory alpha power showed no significant differences across distractibility conditions after STG was stimulated. This indicates that, when the task-irrelevant speech was high in acoustic detail and more challenging to inhibit, parietal alpha oscillators were relied upon more than auditory alpha oscillators to inhibit the distracting auditory information (Wostmann et al., 2017; Herrmann et al., 2022). Whilst we are unable to associate increased parietal alpha power with improved auditory working memory abilities in the current study, future research should continue to build on these findings to investigate the functional role of alpha activity in the context of speech-in-noise perception, and how these patterns of alpha activity change depending on the speech perception strategies utilised by younger and older adults.

Differences in parietal alpha power between TMS Locations and Distractibility conditions were only evident in older adults.

Through analysing parietal alpha power, a significant three-way interaction was found between Age, TMS Location and Distractibility condition. This three-way interaction appears to be driven by older adults – specifically, in the most distracting, 32-channel vocoded conditions, older adults produced a greater parietal alpha power after stimulation to P4 than stimulation to Cz or STG. In contrast, younger adults displayed no differences in parietal alpha power across TMS locations in the High Distractibility conditions. Once again, we believe that this highlights the increased cognitive resources required by older adults to inhibit the processing of task-irrelevant speech that is high in acoustic detail (Wostmann et al., 2017), compared to the resources required by younger adults. If younger adults found the irrelevant speech paradigm less cognitively-demanding than older adults, or were less motivated to produce their most accurate digit recall performance (Ryan & Campbell, 2021), this could have resulted in younger adults producing similar increases in parietal alpha power across TMS locations and Distractibility conditions.

In addition, previous research suggests that younger and older adults may rely upon different neural strategies for perceiving speech. Specifically, it has been posited that if parietal alpha oscillators become less effective for inhibition with healthy ageing, older adults may instead rely upon auditory alpha oscillators, to facilitate attention to target speech

(Hermann et al., 2022). Indeed, the findings of the current study may point to younger and older adults using different strategies to perceive speech – as discussed, the fact that only older adults showed significant differences in parietal and auditory alpha power across TMS Locations and Distractibility conditions may indicate the increased involvement of wider cortical networks for perceiving speech, compared to younger adults. However, the current data do not support the theory that parietal oscillators are less effective in older adults – indeed, it may be the case that an increased reliance on parietal alpha oscillators, compared to younger adults, preserved speech perception performance in older adults. This could be a positive indication that older adults may be more robust to age-related changes in auditory working memory and attentional control than once thought, developing compensatory mechanisms in light of age-related declines in sensory processing to produce a behavioural performance similar to that of younger adults. Future research paradigms should continue to investigate the theory that younger and older adults may rely on alpha oscillators in different brain regions to perceive speech; this could provide a neural indication of the age-related changes in the strategies used to attend and retain relevant speech amongst background distractors.

Younger and older adults displayed differential relationships between alpha and gamma power across brain regions

Previous research suggests that increases in parietal and auditory alpha activity, associated with top-down attentional control, may be able to modulate higher-frequency gamma activity, associated with bottom-up sensory processing. In theory, this could provide important indications of the complex interplay between perceptual and cognitive mechanisms during speech perception, and the role of higher-level cortical brain regions in allocating attentional resources to processing target speech and inhibiting the processing of irrelevant speech. Whilst much of this research has been conducted within the visual system, it was also important to investigate whether such interactions could be applied to any cortical brain region (Mazaheri et al., 2014; Misselhorn et al., 2019).

The current study supported the theory that increases in alpha power may interact with alternative frequency bands like gamma to modulate perception. The exploratory correlational analyses revealed that in younger adults only, there were significant positive relationships between auditory alpha power and auditory gamma power in all TMS locations. This positive relationship may be surprising considering that an increase in alpha activity is believed to modulate, or suppress, gamma activity through pulsed inhibition (Mazaheri et al., 2014; Mathewson et al., 2011; Jensen & Mazaheri et al., 2010). However, it provides interesting insights into the potential alternative role of alpha-gamma coupling in working memory. For example, Mo et al. (2011) administered a visual and auditory selective attention task to macaque monkeys, in which they were required to attend to stimuli in the relevant domain and suppress stimuli in the unattended domain – the researchers analysed the relationship between alpha and gamma power in the inferior temporal cortex, a key neural module within the working memory network involved in maintaining task-relevant information (Miller & Desimone, 1994; Mo et al., 2011). It was found that a positive correlation existed between pre-stimulus alpha power and the stimulus-evoked gamma response, potentially indicative of the role of alpha activity in representing information maintained in working memory (Mo et al., 2011; Palva & Palva, 2007). Mo et al. (2011) suggested that increased alpha power reflects better representation of sensory information in working memory, which leads to better matching between sensory input and working memory content, as reflected in increased gamma activity (Herrmann et al., 2004). We acknowledge that Mo et al. (2011) implemented a different experimental paradigm to the current study; nevertheless, as opposed to decreases in auditory alpha power reflecting the facilitation of attention towards target stimuli, perhaps the interlinked increases in alpha and gamma power in auditory cortex reflect the ability to maintain task-relevant information in younger adults. Future research may focus on investigating the conditions under which the directionality of alpha-gamma coupling may differ, and how the strength of this relationship may change with healthy ageing.

Indeed, crucially, the correlational analyses revealed that younger adults displayed positive relationships within each TMS location, and older adults displayed no significant relationships. Without behavioural data to mirror these effects, the functional role of the age-related changes in the strength of alpha-gamma coupling cannot be concluded. However, it is fair to suggest that younger adults may exhibit stronger alpha-gamma coupling in the auditory cortex compared to older adults; according to the above research, this may support strong working memory performance in younger adults, with reduced alpha-gamma coupling in older adults' auditory cortex being a potential indicator of weaker working memory. Further research is required in this interesting area to explore how the positive and negative relationships in alpha-gamma coupling may both support working memory processes across sensory domains (Mo et al., 2011).

It is also important to note that studies which have found inverse relationships between alpha and gamma, and concluded that alpha-gamma coupling reflects the top-down modulation of sensory processing, have focussed on conducting phase-amplitude coupling analyses, as opposed to the power-power coupling analyses conducted in the current study.

Phase-amplitude coupling analyses have indicated that the phase of alpha oscillations can modulate the amplitude of gamma oscillations, predominantly within the visual system. That is, when alpha power increases, this is associated with stronger suppression of gamma power in the alpha trough (Bonneford & Jensen, 2015). Power-power analyses remain a valid and useful way of investigating cross-frequency coupling, providing advantages for characterising the overarching structure of interactions between different frequency bands (Menceloglu et al., 2020); however, perhaps the improved temporal precision of phase-amplitude coupling analyses (Menceloglu et al., 2020) could uncover more about how alpha and gamma oscillations may interact to support the top-down modulation of sensory processing during speech perception.

Furthermore, as mentioned, much of the investigation into the role of alpha-gamma coupling in modulating sensory processing has taken place within the visual domain; despite the well-established role of alpha activity in functional inhibition, perhaps alternative frequency bands may interact with gamma activity within the auditory domain. For example, a growing amount of evidence has identified coupling between theta (3-7Hz) and gamma oscillations within the auditory cortex as a key mechanism involved in speech perception, with syllabic tracking mechanisms, as indexed by theta phase, modulating phonemic sampling across time, as indexed by gamma amplitude (Giraud & Poeppel, 2012; Hyafil et al., 2015; Lizarazu et al., 2023). Not only is theta-gamma coupling implicated in these bottom-up components of speech perception, but there is also evidence to suggest that theta-gamma interactions are associated with working memory performance (Canolty et al., 2006; Biel et al., 2021; Bahramisharif et al., 2018; Abubaker et al., 2021), particularly in parietal and frontal brain regions. Specifically, working memory retrieval is believed to occur during theta peaks, whereas working memory encoding occurs within theta troughs (Rizzuto et al., 2006;

Abubaker et al., 2021). Taken together, whilst analyses of alpha activity remains an incredibly important line of investigation in uncovering how attentional and working memory mechanisms support speech perception, it is clear that the role of all neural oscillations in cognitive and memory processes must be examined (Hsieh & Ranganath, 2014; Abubaker et al., 2021), in order to build a comprehensive account as to how task-relevant speech is attended to and maintained, whilst distracting speech is inhibited.

Directions for future research and clinical implications

Crucially, the finding that alpha-TMS can modulate parietal and auditory alpha power may have important therapeutic implications, particularly with regards to improving the speech perception abilities of older adults. For example, brain stimulation has already been effectively implemented in clinical practice to treat conditions like depression (Perera et al., 2016; Fitzgerald et al., 2020), and recent technological advances have enabled the treatment of depression via brain stimulation to take place at patients' own homes (Woodham et al., 2023; Sobral et al., 2022; Flow Neuroscience, 2024). Whilst these treatments are still in their clinical infancy, it raises the question of whether the same principles of brain stimulation can be applied to hearing health. For example, if alpha-TMS can entrain parietal and auditory alpha oscillators, perhaps hearing technology companies can develop a wearable brain stimulation device that can deliver TMS pulses to auditory and parietal brain regions, for use by older adults who may experience increased difficulties in inhibiting distracting speech. Future research should focus on establishing causal brain-behavioural links between alpha entrainment and improved inhibitory abilities during speech perception to support the development of such technologies, in the hope that TMS can be used as a therapeutic intervention to strengthen speech perception in older adults. In everyday life settings, this may improve an older adult's ability to suppress the processing of distracting, task-irrelevant auditory information that may impede their speech perception abilities.

6.7. Conclusion

To conclude, age-related changes in auditory working memory and attentional control can have a significant impact on an older adult's ability to perceive speech. However, in the current study, older adults and younger adults produced a similar behavioural performance in an irrelevant speech paradigm; this may be reflective of the compensatory neural mechanisms relied upon by older adults to perceive speech, despite any age-related declines in sensory processing or top-down attentional control. Potential differences in listening effort and motivation levels between age groups were also discussed. In contrast to the behavioural data, analyses of parietal and auditory alpha power revealed differences between younger and older adults across experimental conditions. Crucially, this study demonstrated that TMS, set at a participant's individual alpha frequency, is capable of entraining alpha oscillators in parietal and auditory brain regions to boost alpha activity. Future research paradigms could focus on implementing TMS with different behavioural tasks, to uncover the functional effects that entraining alpha oscillations in domain-general or domain-specific brain regions may have on the top-down mechanisms involved in speech perception. It is also important to continue to investigate how alpha activity may interact with oscillations in different frequency bands, such as gamma activity, to develop our understanding of the interplay between bottom-up sensory processing and top-down auditory working memory during speech perception. Investigating these brain-behaviour links could have important implications for our understanding of how alpha activity may change as a function of healthy ageing, and whether neuromodulation can be used to improve the speech perception abilities of older adults in their everyday lives.

References

Abubaker, M., Al Qasem, W., & Kvašňák, E. (2021). Working memory and cross-frequency coupling of neuronal oscillations. *Frontiers in psychology*, *12*, 756661.

Anderson, S., White-Schwoch, T., Parbery-Clark, A., & Kraus, N. (2013). A dynamic auditory-cognitive system supports speech-in-noise perception in older adults. *Hearing research*, *300*, 18-32.

Awh, E., Vogel, E. K., & Oh, S. H. (2006). Interactions between attention and working memory. *Neuroscience*, *139*(1), 201-208.

Baddeley, A. (2000). The episodic buffer: a new component of working memory?. *Trends in cognitive sciences*, *4*(11), 417-423.

Baddeley, A. D., Emslie, H., & Nimmo-Smith, I. (1992). *The speed and capacity of language-processing test*. Thames Valley Test Company.

Bahramisharif, A., Jensen, O., Jacobs, J., & Lisman, J. (2018). Serial representation of items during working memory maintenance at letter-selective cortical sites. *PLoS biology*, *16*(8), e2003805.

Bell, R., Buchner, A., & Mund, I. (2008). Age-related differences in irrelevant-speech effects. *Psychology and aging*, *23*(2), 377.

Biel, A. L., Minarik, T., & Sauseng, P. (2021). EEG cross-frequency phase synchronization as an index of memory matching in visual search. *NeuroImage*, *235*, 117971.

Bonnefond, M., & Jensen, O. (2015). Gamma activity coupled to alpha phase as a mechanism for top-down controlled gating. *PloS one*, *10*(6), e0128667.

Borghini, G., Candini, M., Filannino, C., Hussain, M., Walsh, V., Romei, V., ... & Cappelletti, M. (2018). Alpha oscillations are causally linked to inhibitory abilities in ageing. *Journal of Neuroscience*, *38*(18), 4418-4429.

British Society of Audiology. (2018, August). *Recommended Procedure: Pure-tone air-conduction and boneconduction threshold audiometry with and without masking.* Available online: https://www.thebsa.org.uk/wp-content/uploads/2018/11/OD104-32-Recommended-Procedure-Pure-Tone-Audiometry-August-2018-FINAL-1.pdf

Buzsáki, G., & Wang, X. J. (2012). Mechanisms of gamma oscillations. *Annual review of neuroscience*, *35*(1), 203-225.

Canolty, R. T., & Knight, R. T. (2010). The functional role of cross-frequency coupling. *Trends in cognitive sciences*, *14*(11), 506-515.

Canolty, R. T., Edwards, E., Dalal, S. S., Soltani, M., Nagarajan, S. S., Kirsch, H. E., ... & Knight, R. T. (2006). High gamma power is phase-locked to theta oscillations in human neocortex. *science*, *313*(5793), 1626-1628.

Cardin, V. (2016). Effects of aging and adult-onset hearing loss on cortical auditory regions. *Frontiers in Neuroscience*, *10*, 199.

Coffey, E. B., Chepesiuk, A. M., Herholz, S. C., Baillet, S., & Zatorre, R. J. (2017). Neural correlates of early sound encoding and their relationship to speech-in-noise perception. *Frontiers in neuroscience*, *11*, 479.

Colle, H. A., & Welsh, A. (1976). Acoustic masking in primary memory. *Journal of verbal learning and verbal behavior*, *15*(1), 17-31.

Corcoran, A. W., Alday, P. M., Schlesewsky, M., & Bornkessel-Schlesewsky, I. (2018). Toward a reliable, automated method of individual alpha frequency (IAF) quantification. *Psychophysiology*, *55*(7), e13064.

Cosh, S., Helmer, C., Delcourt, C., Robins, T. G., & Tully, P. J. (2019). Depression in elderly patients with hearing loss: current perspectives. *Clinical interventions in aging*, 1471-1480.

Cowan, N. (1998). Visual and auditory working memory capacity. *Trends in cognitive sciences*, *2*(3), 77.

Daume, J., Gruber, T., Engel, A. K., & Friese, U. (2017). Phase-amplitude coupling and long-range phase synchronization reveal frontotemporal interactions during visual working memory. *Journal of Neuroscience*, *37*(2), 313-322.

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of neuroscience methods*, *134*(1), 9-21.

Delorme, A., Sejnowski, T., & Makeig, S. (2007). Enhanced detection of artifacts in EEG data using higher-order statistics and independent component analysis. *Neuroimage*, *34*(4), 1443-1449.

Dey, A., & Sommers, M. S. (2015). Age-related differences in inhibitory control predict audiovisual speech perception. *Psychology and aging*, *30*(3), 634.

Diaz, M. T., Johnson, M. A., Burke, D. M., Truong, T. K., & Madden, D. J. (2019). Age-related differences in the neural bases of phonological and semantic processes in the context of task-irrelevant information. *Cognitive, Affective, & Behavioral Neuroscience*, *19*, 829-844.

Dimitrijevic, A., Smith, M. L., Kadis, D. S., & Moore, D. R. (2019). Neural indices of listening effort in noisy environments. *Scientific Reports*, *9*(1), 11278.

Dimitrijevic, A., Smith, M. L., Kadis, D. S., & Moore, D. R. (2017). Cortical alpha oscillations predict speech intelligibility. *Frontiers in human neuroscience*, *11*, 88.

Draheim, C., Pak, R., Draheim, A. A., & Engle, R. W. (2022). The role of attention control in complex real-world tasks. *Psychonomic Bulletin & Review*, *29*(4), 1143-1197.

Ellermeier, W., Kattner, F., Ueda, K., Doumoto, K., & Nakajima, Y. (2015). Memory disruption by irrelevant noise-vocoded speech: Effects of native language and the number of frequency bands. *The Journal of the Acoustical Society of America*, *138*(3), 1561-1569.

Faulkner, A., Rosen, S., & Wilkinson, L. (2001). Effects of the number of channels and speech-to-noise ratio on rate of connected discourse tracking through a simulated cochlear implant speech processor. *Ear and hearing*, *22*(5), 431-438.

Fitzgerald, P. B. (2020). An update on the clinical use of repetitive transcranial magnetic stimulation in the treatment of depression. *Journal of Affective Disorders*, *276*, 90-103.

Flow Neuroscience. (October, 2024). *Research – Flow treatment for depression.* https://www.flowneuroscience.com/research/

Frank, D. J., Nara, B., Zavagnin, M., Touron, D. R., & Kane, M. J. (2015). Validating older adults' reports of less mind-wandering: An examination of eye movements and dispositional influences. *Psychology and Aging*, *30*(2), 266.

Frtusova, J. B., & Phillips, N. A. (2016). The auditory-visual speech benefit on working memory in older adults with hearing impairment. *Frontiers in Psychology*, *7*, 490.

Gaffney, C. J., Drinkwater, A., Joshi, S. D., O'Hanlon, B., Robinson, A., Sands, K. A., ... & Nuttall, H. E. (2021). Short-term immobilization promotes a rapid loss of motor evoked potentials and strength that is not rescued by rTMS treatment. *Frontiers in human neuroscience*, *15*, 640642.

Gazzaley, A., Clapp, W., Kelley, J., McEvoy, K., Knight, R. T., & D'Esposito, M. (2008). Age-related top-down suppression deficit in the early stages of cortical visual memory processing. *Proceedings of the National Academy of Sciences*, *105*(35), 13122-13126.

Gazzaley, A., Cooney, J. W., Rissman, J., & D'esposito, M. (2005). Top-down suppression deficit underlies working memory impairment in normal aging. *Nature neuroscience*, *8*(10), 1298-1300.

Getzmann, S., & Wascher, E. (2017). Visually guided auditory attention in a dynamic "cocktail-party" speech perception task: ERP evidence for age-related differences. *Hearing research*, *344*, 98-108.

Getzmann, S., Golob, E. J., & Wascher, E. (2016). Focused and divided attention in a simulated cocktail-party situation: ERP evidence from younger and older adults. *Neurobiology of aging*, *41*, 138-149.

Getzmann, S., Wascher, E., & Falkenstein, M. (2015). What does successful speech-in-noise perception in aging depend on? Electrophysiological correlates of high and low performance in older adults. *Neuropsychologia*, *70*, 43-57.

Giraud, A. L., & Poeppel, D. (2012). Cortical oscillations and speech processing: emerging computational principles and operations. *Nature neuroscience*, *15*(4), 511-517.

Glim, S., Okazaki, Y. O., Nakagawa, Y., Mizuno, Y., Hanakawa, T., & Kitajo, K. (2019). Phase-Amplitude Coupling of Neural Oscillations Can Be Effectively Probed with Concurrent TMS-EEG. *Neural plasticity*, *2019*(1), 6263907.

Grose, J. H., & Mamo, S. K. (2010). Processing of temporal fine structure as a function of age. *Ear and hearing*, *31*(6), 755-760.

Harris, K. C., Wilson, S., Eckert, M. A., & Dubno, J. R. (2012). Human evoked cortical activity to silent gaps in noise: effects of age, attention, and cortical processing speed. *Ear and hearing*, *33*(3), 330-339.

Henry, M. J., Herrmann, B., Kunke, D., & Obleser, J. (2017). Aging affects the balance of neural entrainment and top-down neural modulation in the listening brain. *Nature communications*, *8*(1), 15801.

Herrmann, B., Maess, B., Henry, M. J., Obleser, J., & Johnsrude, I. S. (2022). Age-related changes in the neural mechanics of dynamic auditory attention in time. *bioRxiv*, 2022-04.

Herrmann, C. S., Munk, M. H., & Engel, A. K. (2004). Cognitive functions of gamma-band activity: memory match and utilization. *Trends in cognitive sciences*, *8*(8), 347-355.

Hsieh, L. T., & Ranganath, C. (2014). Frontal midline theta oscillations during working memory maintenance and episodic encoding and retrieval. *Neuroimage*, *85*, 721-729.

Hyafil, A., Fontolan, L., Kabdebon, C., Gutkin, B., & Giraud, A. L. (2015). Speech encoding by coupled cortical theta and gamma oscillations. *elife*, *4*, e06213.

Jansen, A. P., van Hout, H. P., Nijpels, G., van Marwijk, H. W., Gundy, C., de Vet, H. C., & Stalman, W. A. (2008). Self-reports on the IQCODE in older adults: a psychometric evaluation. *Journal of geriatric psychiatry and neurology*, *21*(2), 83-92.

Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Frontiers in human neuroscience*, *4*, 186.

Jensen, O., Gips, B., Bergmann, T. O., & Bonnefond, M. (2014). Temporal coding organized by coupled alpha and gamma oscillations prioritize visual processing. *Trends in neurosciences*, *37*(7), 357-369.

Jorm, A. F. (2004). The Informant Questionnaire on cognitive decline in the elderly (IQCODE): a review. *International psychogeriatrics*, *16*(3), 275-293.

Kaiser, J. (2015). Dynamics of auditory working memory. *Frontiers in psychology*, *6*, 613.

Keil, J., & Senkowski, D. (2018). Neural oscillations orchestrate multisensory processing. *The Neuroscientist*, *24*(6), 609-626.

Kelly, S. P., Lalor, E. C., Reilly, R. B., & Foxe, J. J. (2006). Increases in alpha oscillatory power reflect an active retinotopic mechanism for distracter suppression during sustained visuospatial attention. *Journal of neurophysiology*, *95*(6), 3844-3851.

Lange, J., Keil, J., Schnitzler, A., van Dijk, H., & Weisz, N. (2014). The role of alpha oscillations for illusory perception. *Behavioural brain research*, *271*, 294-301.

Lawrence, B. J., Jayakody, D. M., Bennett, R. J., Eikelboom, R. H., Gasson, N., & Friedland, P. L. (2020). Hearing loss and depression in older adults: a systematic review and meta-analysis. *The Gerontologist*, *60*(3), e137-e154.

Liberman, M. C., & Kujawa, S. G. (2017). Cochlear synaptopathy in acquired sensorineural hearing loss: Manifestations and mechanisms. *Hearing research*, *349*, 138-147.

Lizarazu, M., Carreiras, M., & Molinaro, N. (2023). Theta-gamma phase-amplitude coupling in auditory cortex is modulated by language proficiency. *Human brain mapping*, *44*(7), 2862-2872.

Maeda, F., Keenan, J. P., Tormos, J. M., Topka, H., & Pascual-Leone, A. (2000). Modulation of corticospinal excitability by repetitive transcranial magnetic stimulation. *Clinical neurophysiology*, *111*(5), 800-805.

Mathewson, K. E., Lleras, A., Beck, D. M., Fabiani, M., Ro, T., & Gratton, G. (2011). Pulsed out of awareness: EEG alpha oscillations represent a pulsed-inhibition of ongoing cortical processing. *Frontiers in psychology*, *2*, 99.

Mazaheri, A., van Schouwenburg, M. R., Dimitrijevic, A., Denys, D., Cools, R., & Jensen, O. (2014). Region-specific modulations in oscillatory alpha activity serve to facilitate processing in the visual and auditory modalities. *Neuroimage*, *87*, 356-362.

McMahon, C. M., Boisvert, I., De Lissa, P., Granger, L., Ibrahim, R., Lo, C. Y., ... & Graham, P. L. (2016). Monitoring alpha oscillations and pupil dilation across a performance-intensity function. *Frontiers in Psychology*, *7*, 745.

Menceloglu, M., Grabowecky, M., & Suzuki, S. (2020). Spectral-power associations reflect amplitude modulation and within-frequency interactions on the sub-second timescale and cross-frequency interactions on the seconds timescale. *Plos one*, *15*(5), e0228365.

Misselhorn, J., Friese, U., & Engel, A. K. (2019). Frontal and parietal alpha oscillations reflect attentional modulation of cross-modal matching. *Scientific reports*, *9*(1), 5030.

Murphy, D. R., Bailey, H., Pearson, M., & Albert, G. (2018). The irrelevant speech effect among younger and older adults: The influence of background noises on reading comprehension. *Experimental aging research*, *44*(2), 162-178.

Mo, J., Schroeder, C. E., & Ding, M. (2011). Attentional modulation of alpha oscillations in macaque inferotemporal cortex. *Journal of Neuroscience*, *31*(3), 878-882.

Mukaka, M. M. (2012). A guide to appropriate use of correlation coefficient in medical research. *Malawi medical journal*, *24*(3), 69-71.

Mutanen, T. P., Biabani, M., Sarvas, J., Ilmoniemi, R. J., & Rogasch, N. C. (2020). Source-based artifact-rejection techniques available in TESA, an open-source TMS–EEG toolbox. *Brain Stimulation: Basic, Translational, and Clinical Research in Neuromodulation*, *13*(5), 1349-1351.

Nikolić, D., Fries, P., & Singer, W. (2013). Gamma oscillations: precise temporal coordination without a metronome. *Trends in cognitive sciences*, *17*(2), 54-55.

Noda, T., Kanzaki, R., & Takahashi, H. (2013). Stimulus phase locking of cortical oscillation for auditory stream segregation in rats. *PLoS One*, *8*(12), e83544.

Noyce, A. L., Varghese, L., Mathias, S. R., & Shinn-Cunningham, B. G. (2024). Perceptual organization and task demands jointly shape auditory working memory capacity. *JASA Express Letters*, *4*(3).

Obleser, J., Wöstmann, M., Hellbernd, N., Wilsch, A., & Maess, B. (2012). Adverse listening conditions and memory load drive a common alpha oscillatory network. *Journal of Neuroscience*, *32*(36), 12376-12383.

Palva, S., & Palva, J. M. (2007). New vistas for α-frequency band oscillations. *Trends in neurosciences*, *30*(4), 150-158.

Pascual-Leone, A., Valls-Solé, J., Wassermann, E. M., & Hallett, M. (1994). Responses to rapid-rate transcranial magnetic stimulation of the human motor cortex. *Brain*, *117*(4), 847-858.

Peelle, J. E., Troiani, V., Grossman, M., & Wingfield, A. (2011). Hearing loss in older adults affects neural systems supporting speech comprehension. *Journal of neuroscience*, *31*(35), 12638-12643.

Peelle, J. E., Troiani, V., Wingfield, A., & Grossman, M. (2010). Neural processing during older adults' comprehension of spoken sentences: age differences in resource allocation and connectivity. *Cerebral cortex*, *20*(4), 773-782.

Pepper, J. L., & Nuttall, H. E. (2023). Age-related changes to multisensory integration and audiovisual speech perception. *Brain Sciences*, *13*(8), 1126.

Perera, T., George, M. S., Grammer, G., Janicak, P. G., Pascual-Leone, A., & Wirecki, T. S. (2016). The clinical TMS society consensus review and treatment recommendations for TMS therapy for major depressive disorder. *Brain stimulation*, *9*(3), 336-346.

Pichora-Fuller, M. K., Alain, C., & Schneider, B. A. (2017). Older adults at the cocktail party. *The auditory system at the cocktail party*, 227-259.

Pichora-Fuller, M. K., Schneider, B. A., & Daneman, M. (1995). How young and old adults listen to and remember speech in noise. *The Journal of the Acoustical Society of America*, *97*(1), 593-608.

Reinhart, R. M., & Nguyen, J. A. (2019). Working memory revived in older adults by synchronizing rhythmic brain circuits. *Nature neuroscience*, *22*(5), 820-827.

Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current directions in psychological science*, *17*(3), 177-182.

Reuter-Lorenz, P. A., & Lustig, C. (2005). Brain aging: reorganizing discoveries about the aging mind. *Current opinion in neurobiology*, *15*(2), 245-251.

Rizzuto, D. S., Madsen, J. R., Bromfield, E. B., Schulze-Bonhage, A., & Kahana, M. J. (2006). Human neocortical oscillations exhibit theta phase differences between encoding and retrieval. *Neuroimage*, *31*(3), 1352-1358.

Rogasch, N. C., Sullivan, C., Thomson, R. H., Rose, N. S., Bailey, N. W., Fitzgerald, P. B., ... & Hernandez-Pavon, J. C. (2017). Analysing concurrent transcranial magnetic stimulation and electroencephalographic data: A review and introduction to the open-source TESA software. *Neuroimage*, *147*, 934-951.

Ross, B., & Fujioka, T. (2016). 40-Hz oscillations underlying perceptual binding in young and older adults. *Psychophysiology*, *53*(7), 974-990.

Rossi, S., Hallett, M., Rossini, P. M., Pascual-Leone, A., & Safety of TMS Consensus Group. (2009). Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research. *Clinical neurophysiology*, *120*(12), 2008-2039.

Roux, F., Wibral, M., Singer, W., Aru, J., & Uhlhaas, P. J. (2013). The phase of thalamic alpha activity modulates cortical gamma-band activity: evidence from resting-state MEG recordings. *Journal of Neuroscience*, *33*(45), 17827-17835.

Rufener, K. S., Oechslin, M. S., Wöstmann, M., Dellwo, V., & Meyer, M. (2016). Age-related neural oscillation patterns during the processing of temporally manipulated speech. *Brain topography*, *29*, 440-458.

Ryan, A. D., & Campbell, K. L. (2021). The ironic effect of older adults' increased task motivation: Implications for neurocognitive aging. *Psychonomic Bulletin & Review*, *28*(6), 1743-1754.

Sander, M. C., Werkle-Bergner, M., & Lindenberger, U. (2012). Amplitude modulations and inter-trial phase stability of alpha-oscillations differentially reflect working memory constraints across the lifespan. *Neuroimage*, *59*(1), 646-654.

Scholz, P. F., Spitz, R. M., von Neuforn, C. M. S., & TV, L. (2023). WHISPERED SPEECH CAUSES DISRUPTION OF SERIAL SHORT-TERM MEMORY. *FECHNER DAY 2023*, 104.

Seifi Ala, T., Graversen, C., Wendt, D., Alickovic, E., Whitmer, W. M., & Lunner, T. (2020). An exploratory study of EEG alpha oscillation and pupil dilation in hearing-aid users during effortful listening to continuous speech. *Plos one*, *15*(7), e0235782.

Seli, P., Maillet, D., Smilek, D., Oakman, J. M., & Schacter, D. L. (2017). Cognitive aging and the distinction between intentional and unintentional mind wandering. *Psychology and aging*, *32*(4), 315.

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Measurement of attentional reserve and mental effort for cognitive workload assessment under various task demands during dual-task walking. *Biological psychology*, *134*, 39-51.

Slade, K., Plack, C. J., & Nuttall, H. E. (2020). The effects of age-related hearing loss on the brain and cognitive function. *Trends in Neurosciences*, *43*(10), 810-821.

Sobral, M., Guiomar, R., Martins, V., & Ganho-Ávila, A. (2022). COMBINING APP-BASED PSYCHOLOGICAL INTERVENTION WITH HOME-BASED TRANSCRANIAL DIRECT STIMULATION FOR THE TREATMENT OF DEPRESSIVE AND ANXIETY SYMPTOMS: A CASE SERIES. *Psychiatria Danubina*, *34*(suppl 3), 20-20.

Stokes, M. G., Chambers, C. D., Gould, I. C., English, T., McNaught, E., McDonald, O., & Mattingley, J. B. (2007). Distance-adjusted motor threshold for transcranial magnetic stimulation. *Clinical Neurophysiology*, *118*(7), 1617-1625.

Thut, G., Veniero, D., Romei, V., Miniussi, C., Schyns, P., & Gross, J. (2011). Rhythmic TMS causes local entrainment of natural oscillatory signatures. *Current biology*, *21*(14), 1176-1185.

Tremblay, P., Brisson, V., & Deschamps, I. (2021). Brain aging and speech perception: Effects of background noise and talker variability. *NeuroImage*, *227*, 117675.

Trillenberg, P., Bremer, S., Oung, S., Erdmann, C., Schweikard, A., & Richter, L. (2012). Variation of stimulation intensity in transcranial magnetic stimulation with depth. *Journal of neuroscience methods*, *211*(2), 185-190.

Tun, P. A., O'Kane, G., & Wingfield, A. (2002). Distraction by competing speech in young and older adult listeners. *Psychology and aging*, *17*(3), 453.

Tzvi, E., Bauhaus, L. J., Kessler, T. U., Liebrand, M., Wöstmann, M., & Krämer, U. M. (2018). Alpha-gamma phase amplitude coupling subserves information transfer during perceptual sequence learning. *Neurobiology of learning and memory*, *149*, 107-117.

Van Dijk, H., Nieuwenhuis, I. L., & Jensen, O. (2010). Left temporal alpha band activity increases during working memory retention of pitches. *European Journal of Neuroscience*, *31*(9), 1701-1707.

Van Kerkoerle, T., Self, M. W., Dagnino, B., Gariel-Mathis, M. A., Poort, J., Van Der Togt, C., & Roelfsema, P. R. (2014). Alpha and gamma oscillations characterize feedback and feedforward processing in monkey visual cortex. *Proceedings of the National Academy of Sciences*, *111*(40), 14332-14341.

Wong, P. C., Jin, J. X., Gunasekera, G. M., Abel, R., Lee, E. R., & Dhar, S. (2009). Aging and cortical mechanisms of speech perception in noise. *Neuropsychologia*, *47*(3), 693-703.

Woodham, R. D., Selvaraj, S., Lajmi, N., Hobday, H., Sheehan, G., Ghazi-Noori, A. R., ... & Fu, C. H. (2023). Home-based transcranial direct current stimulation RCT in major depression. *medRxiv*, 2023-11.

Wöstmann, M., & Obleser, J. (2016). Acoustic detail but not predictability of task-irrelevant speech disrupts working memory. *Frontiers in human neuroscience*, *10*, 538.

Wöstmann, M., Herrmann, B., Wilsch, A., & Obleser, J. (2015). Neural alpha dynamics in younger and older listeners reflect acoustic challenges and predictive benefits. *Journal of Neuroscience*, *35*(4), 1458-1467.

Wöstmann, M., Lim, S. J., & Obleser, J. (2017). The human neural alpha response to speech is a proxy of attentional control. *Cerebral cortex*, *27*(6), 3307-3317.

Zaehle, T., Rach, S., & Herrmann, C. S. (2010). Transcranial alternating current stimulation enhances individual alpha activity in human EEG. *PloS one*, *5*(11), e13766.

Zhang, Z., Mai, Y., Yang, M., & Zhang, M. Z. (2018). Package 'WebPower'. *Basic and advanced statistical power analysis version*, *72*, 555.

Zoefel, B., & Davis, M. H. (2017). Transcranial electric stimulation for the investigation of speech perception and comprehension. *Language, Cognition and Neuroscience*, *32*(7), 910-923.

7. General Discussion

7.1. Summary of studies

Age-related changes in the top-down and bottom-up mechanisms of multisensory integration – such as temporal processing and attentional control – are believed to significantly affect an older adult's perception of, and navigation through, their environment (Talsma et al., 2010; Mozolic et al., 2008; Bedard & Barnett-Cowan, 2016). Namely, weaker top-down modulation of audiovisual processing may be associated with both their difficulties in speech perception (Getzmann et al., 2016; Getzmann et al., 2017) and balance maintenance (Ozdemir et al., 2018; Edwards et al., 2018). Given our increasingly ageing population, it is imperative that cognitive neuroscientists develop a deeper understanding of how the efficacy of these attentional mechanisms may decline as a function of healthy ageing. The most comprehensive understanding will come from identifying the neural correlates of the perceptual and cognitive mechanisms involved in multisensory processing, and comparing how these differ between younger and older adults. From this, treatments and interventions could be explored to strengthen attentional control and improve the accuracy of multisensory integration in older adults, in a bid to improve older adults' perception of our dynamic, everyday environments. This thesis investigated how the cognitive and perceptual mechanisms involved in multisensory integration change as a function of healthy ageing, how this is reflected in oscillatory neural activity, and the impact of such changes on an older adult's speech perception and balance abilities.

Chapter 2 provided a detailed overview of the existing research surrounding the age-related changes in the bottom-up, perceptual mechanisms and top-down, cognitive mechanisms involved in multisensory integration. Crucially, it was postulated that a key neural correlate underlying these changes – particularly with regards to attentional control – could be oscillations in the alpha-band frequency. The interplay between top-down attentional control and the bottom-up concept of the temporal binding window was investigated further in Chapters 3 and 4. A particular focus was placed on uncovering how this attentional filtering of incoming sensory information may be reflected by age-related changes in alpha activity, and whether increased alpha activity reflected stronger inhibition of task-irrelevant sensory information.

Through identifying the shared top-down and bottom-up mechanisms involved in audiovisual speech perception and balance maintenance (Chapter 2), a comprehensive account was developed as to the significant real-world impact that these changes can have on an older adult's quality of life. That is, less accurate multisensory perception in older adults could be a fundamental contributor to both their weaker speech perception abilities (Chapter 5, Chapter 6) and increased risk of falls (Chapter 4, Chapter 5). It is important to note that in our everyday lives, it is rare that a multisensory task is completed in isolation – attentional resources are often competed for, and must be divided effectively between tasks for successful performance in each. As such, Chapter 5 investigates how younger and older adults may allocate attentional resources during audiovisual speech perception and balance, and whether this allocation is reflected in fluctuations in neural alpha activity.

In previous research, the functional role of neural alpha activity in attentional control has been investigated during behavioural tasks in which relevant sensory information must be attended to, and irrelevant sensory information must be inhibited (Wostmann et al., 2017; Dimitrijevic et al., 2017). Chapters 4-6 of this thesis revealed interesting findings regarding how these patterns of alpha activity and selective attention abilities change with healthy ageing. In order to draw causal links between alpha activity and attentional control during sensory processing, Chapter 6 implemented a TMS-EEG paradigm to entrain alpha oscillators in parietal and auditory brain regions, to assess whether enhancing alpha activity can improve younger and older adults' ability to attend to relevant auditory information and inhibit distracting speech.

Crucially, whilst the previous research detailed in Chapter 2 appears to cast a rather negative light on the impact that age-related changes in multisensory integration may have on older adults' perception and action, this thesis may provide a promising indication that healthy ageing may not have as detrimental an impact on veridical perception as some may think (Chapter 5, Chapter 6). That is, older adults may employ compensatory strategies to preserve their ability to perceive speech and maintain balance, despite challenges such as age-related hearing loss, weaker inhibition, and neurodegeneration of subcortical balance centres.

This general discussion will summarise the key findings of each of the earlier chapters in this thesis, identifying the important contributions of these findings in furthering our understanding of age-related changes in multisensory processing, and the real-world implications for perception and action in the everyday lives of older adults.

7.2. Top-down modulation of multisensory integration across the lifespan.

7.2.1. Summary of main findings

In Chapters 3 and 4, we investigated whether top-down attentional control could narrow the width of the temporal binding window (Donohue et al., 2015; Powers et al., 2012) in younger and older adults. In both chapters, it was found that older adults displayed increased multisensory integration (i.e. weaker attentional control) compared to younger adults, even when the stimuli were within the focus of attention. Whilst we were unable to draw specific conclusions regarding the age-related changes in the width of the temporal binding window, our findings support previous research indicating that older adults exhibit weaker inhibition of task-irrelevant sensory information (Lustig et al., 2007; Pichora-Fuller et al., 2017; Hasher et al., 2007), which results in increased, less accurate multisensory integration. Furthermore, in Chapter 5, we investigated how attentional resources are flexibly allocated between two concurrent multisensory tasks, and how this reallocation may change as a function of healthy ageing – data indicate that whilst older adults do exhibit differences in dual-task attentional control compared to younger adults, speech perception and balance performances may be preserved with healthy ageing, potentially due to an increased reliance on compensatory strategies. Finally, in Chapter 6, we explored whether entraining alpha oscillators could enhance the top-down ability to attend to relevant stimuli and inhibit distracting stimuli. We found that TMS could effectively modulate alpha activity in parietal and auditory brain regions; however, further research is required to uncover the functional relevance of such modulations on the ability to inhibit task-irrelevant information, and how this ability is affected by increasing age. Taken together, this thesis provides valuable contributions to the literature surrounding the role of attentional control in multisensory processing, and indicates that younger and older adults may exhibit differences in attentional control during everyday multisensory tasks like speech perception and balance maintenance.

7.2.2. Weaker attentional control in older adults? Behavioural evidence

The literature review conducted in Chapter 2 identified age-related declines in top-down attentional control as a significant contributor to the increased multisensory integration experienced by older adults, which may negatively impact performance in everyday tasks like speech perception (Dey & Sommers, 2015; Campbell et al., 2020) and balance maintenance (Lajoie et al., 1993; Stapleton et al., 2014). Specifically, older adults may find it more difficult than younger adults to inhibit distracting, task-irrelevant information, which would result in a less accurate perception of their environment (Lustig et al., 2007).

For example, when successful task performance requires the inhibition of task-irrelevant auditory information, older adults may experience increased difficulty in suppressing these sensory inputs and segregating them from concurrent visual stimuli (Fabiani et al., 2006; Stothart & Kazanina, 2016). Chapters 3 and 4 supported this theory; when processing low-level visual and auditory stimuli in the stream-bounce task, older adults exhibited weaker top-down attentional control compared to younger adults and increased, less accurate multisensory integration. However, in Chapters 5 and 6, more complex speech stimuli were implemented in the task; under these conditions, younger and older adults showed no behavioural difference in their ability to inhibit distracting information, producing similar perceptual performances. This highlights how the study of age-related changes in multisensory processing may be task dependent, particularly with regards to the complexity of the stimuli implemented (Bedard & Barnett-Cowan, 2016; Barutchu et al., 2019).

Perhaps in Chapters 5 and 6, older adults were familiar with the challenge of having to perceive speech in noisy listening environments, due to their exposure to such scenarios in everyday life. That is, older adults may have been able to effectively engage the cognitive strategies that they regularly practice in everyday life speech perception (e.g. increased recruitment of cortical resources, increased reliance on semantic context; Arlinger et al., 2009), applying these skills to the laboratory-based tasks and producing a strong behavioural performance. In contrast, the stream-bounce stimuli implemented in Chapters 3 and 4 were more abstract and not encountered in everyday settings; these lower-level stimuli may have, instead, allowed for the behavioural detection of age-related changes in the attentional modulation of temporal processing. Indeed, in previous research implementing simple tasks like the sound-induced flash illusion (Setti et al., 2023; Hernandez et al., 2019; Hirst et al., 2019), age-related changes in audiovisual processing have been apparent (however, see Hugenschmidt et al., 2009). Taken together, this thesis may provide a promising indication that despite the fact that attentional control may weaken with healthy ageing, it may not be as maladaptive for veridical perception as has previously been indicated (Pichora-Fuller et al., 2017; De Dieuleveult et al., 2017; Zhang et al., 2020). However, given that the study of age-related changes in multisensory integration may be susceptible to the effects of task-dependency (Barutchu et al., 2019), perhaps the tasks and measures implemented in Chapters 5 and 6 were not sensitive enough to detect differences in attentional processing between younger and older adults; this is explored further in the limitations section of this discussion. Taken together, it is clear that further research is required to explore the conditions under which younger and older adults may exhibit differences in the top-down modulation of sensory information, in order to build a complete account as to how these differences may manifest in everyday life.

7.2.3. Implications: interventions for speech perception and balance maintenance across the lifespan

A key investigation throughout this thesis was to explore how age-related changes in top-down attentional control could be an underlying factor in the increased, less temporally precise multisensory integration exhibited by older adults. Whilst the ability to attend to target sensory information appears to be preserved in older adults (Talsma et al., 2006; Getzmann et al., 2016), the inhibitory functions associated with top-down attentional control may be weakened with healthy ageing (Getzmann et al., 2016), with older adults finding it more difficult than younger adults to suppress task-irrelevant inputs. Fractionating this notion of attention to relevant inputs and inhibition of irrelevant inputs remains key in future research, particularly with regards to how the functional role of alpha activity may manifest in each mechanism. Indeed, core models in attentional theory such as those posited by Hasher et al. (1991), Neumann & DeSchepper (1991) and Tipper (1985; 1991) identify that separate and distinct excitatory and inhibitory mechanisms within selective attention work in tandem during the processing of relevant and irrelevant information. From this, it would be reductive to argue that top-down attentional control, as a whole, deteriorates with healthy ageing, when findings of Chapters 4, 5 and 6 support the argument that older adults may adopt compensatory strategies (e.g. increased facilitation of attention towards target stimuli; Wostmann et al., 2015; Herrmann et al., 2022; Ozdemir, 2016) to preserve cognitive or motor performance despite declines in inhibition. This compensatory approach is explored further later in this discussion. Future research should continue to build on the findings of this thesis, manipulating bottom-up temporal elements of both low-level and high-level multisensory stimuli and investigating how top-down attentional and inhibitory mechanisms can coordinate to modulate the processing of such stimuli. Fundamentally, the study of how this interplay differs between younger and older adults is crucial in determining its combined impact on an older adult's perception and action.

A more comprehensive understanding of the role of top-down attentional mechanisms in the modulation of multisensory integration could have a significant impact on the treatments and interventions designed to improve an older adult's ability to a) perceive speech in adverse listening conditions and b) reduce risk of falls when balance is compromised. For example, whilst it is agreed that speech-in-noise perception can be improved by increasing attention to target speech and inhibiting the distracting effects of background noise (Bieber & Gordon-Salant, 2021), there is discourse with regards to the most effective approach to achieve this. Auditory training paradigms have aimed to improve the recognition of target speech amongst distractors. For example, word-level training consists of focusing attention on isolated words in the hope that this improves participants’ ability to recognise these words in noise (Burk & Humes, 2007; Burk & Humes, 2008; Bieber & Gordon-Salant, 2021); in contrast, sentence-level training involves focusing attention on acoustic and contextual cues in running speech (Sweetow & Sabes, 2006; Bieber & Gordon-Salant, 2021). Whilst these training paradigms can result in improved task performance in older adults, such learning may be limited to improvements in the specific training stimuli implemented (Bieber & Gordon-Salant, 2021), and therefore may not generalise to improve speech-in-noise perception of untrained everyday stimuli. In other words, whilst such paradigms may elicit near-transfer effects in older adults, far-transfer outcomes in real-world contexts have been less successful (Zelinski et al., 2009; Barnett & Ceci, 2002).

The findings of this thesis would, instead, support the notion that combined auditory-cognitive training paradigms may be the most effective approach to improve the speech perception of older adults. For example, by taxing cognitive load and subsequently strengthening auditory working memory (Gordon-Salant & Cole, 2016; Schurman et al., 2014) and attentional control (Whitton et al., 2014), older adults after training may be better equipped to transfer the skills that they have learned to improve their processing of untrained speech stimuli (Bieber & Gordon-Salant, 2021). For example, Anderson et al. (2013) implemented an auditory-cognitive training paradigm which aimed to improve the temporal precision of speech-in-noise processing. Older adults with hearing loss participated in an 8-week program, in which the duration of formant transitions for consonant-vowel components was adaptively contracted and exaggerated; participants learned to perceive these transitions across a range of exercises designed to increase cognitive load during the listening task, such as discriminating between similar syllables, remembering details from stories, or repeating back syllable and word sequences (Anderson et al., 2013). The older adults who completed this training exhibited improvements in memory performance, processing speed and speech-in-noise perception, as well as faster neural timing, compared to the control group. Such auditory-cognitive training protocols therefore appear effective in improving age-related declines in temporal precision through strengthening top-down cognitive mechanisms, which in turn may support performance in tasks like speech-in-noise perception (Anderson et al., 2013).

Focussing on strengthening cognitive function through these kinds of training paradigms is also highly likely to be effective in improving balance maintenance in older adults. Indeed, physiotherapy techniques such as gait training and leg strengthening exercises have only been moderately successful in reducing fall risk (Parry et al., 2008; Merriman et al., 2015), suggesting that there may be a missing element required in the design of treatments to stabilise balance in older adults. Chapter 4 provided support for the key role of attentional control in balance maintenance, and indicated that this relationship may change with healthy ageing; from this, it would be reasonable to suggest that combined cognitive-motor training to strengthen the attentional control of older adults could reduce fall risk (van het Reve & de Bruin, 2014; Smith-Ray et al., 2015). For example, Barban et al. (2017) detailed a large-scale study in which a sample of older adults completed motor training, involving balance and gait exercises, as well as cognitive training, involving working memory, selective attention and sustained attention tasks. Compared to older adults who only completed cognitive training or only completed motor training, the combined cognitive-motor group exhibited maximal benefits in both mobility and auditory verbal memory immediately after training. The authors therefore highlighted that there is a strong relationship between attentional mechanisms and gait and balance performance (Barban et al., 2017), supporting the notion that both elements should be focussed upon in cognitive-motor training paradigms to improve balance maintenance.

Indeed, Chapters 4 and 5 indicated that older adults may rely upon increased attentional resources for balance maintenance compared to younger adults; improving a fall-prone older adult's ability to flexibly reallocate attentional resources towards balance, as well as their ability to inhibit task-irrelevant information which may detract from these resources, could be an effective technique to support balance maintenance. It is important that these kind of paradigms are tested in randomised control trials before being implemented as potential interventions to improve speech perception and balance in older adults. Nevertheless, the findings of this thesis indicate that age-related deficits in attentional control could be an underlying factor in the weaker speech perception performance and increased risk of falls in older adults; therefore, it would be reasonable to target attentional control as the core mechanism to strengthen during any treatments or interventions to improve older adults' performance in these tasks.

7.3. Neural correlates of age-related changes in attentional control during multisensory processing.

7.3.1. Summary of main findings

Unravelling the complex role of oscillatory alpha activity in attentional control during multisensory processing was a key aim of this thesis, particularly with regards to how such activity differs between younger and older adults. As highlighted in Chapter 2, alpha activity has been investigated in relation to both speech perception and balance maintenance, often using groups of younger adult participants; however, more research is required to understand how age-related changes in attentional control are reflected in alpha activity. Given that both speech perception and balance maintenance may decline with healthy ageing, this thesis aimed to address how fluctuations in alpha activity during each task may differ between younger and older adults.

Chapters 4, 5 and 6 contributed to the literature suggesting that alpha power is a key underlying neural correlate in top-down attentional control – a significant interaction between age and balance ability predicted alpha activity in Chapter 4; significant decreases in fronto-central alpha activity in clear listening environments was found in Chapter 5; and increases in parietal alpha activity during the inhibition of distracting speech high in acoustic detail was found in Chapter 6. However, the role of alpha activity in modulating audiovisual integration, specifically, requires further research, as Chapter 4 revealed that increases in alpha power did not predict the extent of multisensory integration within the task. Crucially, it was important to investigate whether there is anything that we can do, as neuroscientists, to improve attentional control in older adults; Chapter 6 illustrated that entraining alpha oscillators using non-invasive brain stimulation could enhance alpha activity in parietal and auditory brain regions. Whilst this enhancement did not result in changes in auditory working memory during speech perception, it is an important indication that TMS can be used to modulate oscillatory alpha activity. It is hoped that these findings will support the implementation of TMS in future paradigms to improve an older adult's ability to attend to relevant sensory stimuli and inhibit task-irrelevant stimuli, through enhancing alpha activity. The following sections will discuss the importance of studying alpha activity in relation to age-related changes in the top-down modulation of sensory processing, and what we can infer with regards to the role of alpha activity in speech perception and balance maintenance.

7.3.2. Role of alpha activity in attentional control and inhibition

This thesis has cast light on how increases and decreases in alpha power in different brain regions may coordinate to filter the influx of sensory information experienced in everyday life, and how alpha activity may be able to reflect the allocation of attentional resources between concurrent multisensory tasks. Chapter 2 provided a detailed discussion surrounding how neural oscillations in the alpha band have been studied previously with regards to the inhibition of task-irrelevant sensory information. This is particularly important in real-world scenarios such as speech perception, wherein successful performance is dependent on the suppression of distracting background noise (Pichora-Fuller et al., 2017; Getzmann et al., 2015). The findings of Chapter 6 supported previous research conducted by Wostmann and colleagues; in conditions where parietal cortex was stimulated, parietal alpha activity was highest when distracting information was high in acoustic detail; higher alpha power may reflect the increased effort required to suppress this task-irrelevant speech (Wostmann et al., 2017). In addition, older adults within this task produced a greater parietal alpha power than younger adults when attending to relevant speech and inhibiting distracting speech, potentially indicative of the increased cognitive resources required to do so (Peelle et al., 2010; Getzmann et al., 2015). Taken together, we have provided support for the theory that increases in alpha power may reflect the increased inhibition of task-irrelevant, distracting information, and our findings indicate that these patterns of alpha activity may change as a function of healthy ageing.

Whilst increases in alpha activity reflect increases in inhibition, decreases in alpha activity reflect increased neural activation (Shaw et al., 2018). This may be particularly important in relation to fall risk in older adults; due to the age-related deterioration of sensorimotor tracts responsible for automatic balance, it is believed that older adults display an increased reliance on cortical brain regions and higher-level cognitive resources to maintain balance (Ozdemir et al., 2018; Edwards et al., 2018). The findings of Chapter 4 provided support for this, in that increased parieto-occipital alpha power (i.e. increased inhibition) was associated with stronger balance ability in older adults. It is likely that increased inhibition allows for an increased availability of attentional resources to maintain balance, in line with the gating-by-inhibition theories of alpha activity (Jensen & Mazaheri, 2010). In Chapter 5, whilst no significant differences in fronto-central alpha activity were found between easy and challenging stance conditions, the significant main effect of listening condition may indicate how relying on external auditory or visual cues in the environment can serve as an "anchor" to stabilise postural sway (Deviterne et al., 2005). Once again, these could be just two examples of the potential strategies developed by older adults to preserve their motor performance and reduce fall risk. However, it is also important to acknowledge the high physical and cognitive abilities of older adults in each chapter of this thesis, which may significantly improve their ability to flexibly adopt such strategies – the implications for the generalisability of these findings are explored later in the discussion.

7.3.3. Implications: Neuromodulation as a tool to investigate the functional role of neural oscillations

Analysing EEG data can provide valuable insights into the role of alpha activity during the top-down modulation of multisensory integration. A key finding of Chapter 6 is that TMS may be an effective technique to entrain alpha oscillators in different brain regions. We found that stimulating parietal and auditory brain regions at each participant's individual alpha frequency could enhance alpha activity in each of these regions. This is important because if some older adults experience weaker attentional control compared to younger adults, and if these attentional deficits may be reflected in oscillatory alpha activity, then neuromodulation could be used as a potential intervention to boost alpha activity in these older adults, improving their ability to attend to relevant information and inhibit irrelevant information (Wostmann et al., 2015; Wostmann et al., 2017). For example, the scaffolding theory of cognitive ageing (Reuter-Lorenz & Park, 2014) suggests that non-invasive brain stimulation techniques like TMS could enhance neural "scaffolding" – specifically, neuromodulation can be used to increase brain activity, recruit alternative brain regions, and generate new neurons, directly influencing brain structure and function by enhancing functional connectivity (Reuter-Lorenz & Park, 2014; Oosterhuis et al., 2023).

Based on this, perhaps brain stimulation could serve as an effective intervention to promote the use of compensatory brain mechanisms and improve cognitive performance in older adults who may have exhibited attentional deficits before stimulation (Perceval et al., 2020; Oosterhuis et al., 2023). The "gold standard" of such applications would perhaps manifest as portable brain stimulation devices which can entrain neural oscillations without participants attending a lab session (as has previously been implemented as a treatment for depression; Woodham et al., 2023; Sobral et al., 2022). This has the potential to improve an older adult's ability to attend to relevant speech and inhibit distracting speech in everyday conversational environments. However, before the utility of such technology is explored, further research is required to determine the functional relevance of entraining alpha oscillators in auditory working memory and attentional control, as the neural changes induced in Chapter 6 were not reflected in a significant behavioural enhancement, likely due to a lack of sensitivity with regards the behavioural measure used.

It is also important to note that some discourse remains in the literature with regards to where alpha activity may originate during speech perception – from domain-general brain regions associated with the attentional network (Wostmann et al., 2017), or from domain-specific auditory areas associated with speech processing (Dimitrijevic et al., 2017). As such, alongside therapeutic interventions, TMS should continue to be implemented in research paradigms designed to unpick the functional origins of alpha activity within the brain. Our findings from Chapter 6 provide support for the former argument; parietal alpha activity was enhanced in the most distracting listening conditions when the parietal cortex was stimulated, which may indicate the role of parietal alpha activity in inhibition. Whilst such modulations in alpha activity did not appear to impact behavioural responses, these findings can provide valuable contributions to the literature surrounding the fluctuations in alpha activity during complex sensory processing like speech perception, and can serve as a basis for future research investigating the how such fluctuations may impact attention and inhibition.

7.4. Cognitive flexibility and compensatory strategies to preserve multisensory function in healthy ageing.

7.4.1. Summary of main findings

The literature review conducted in Chapter 2 portrays a rather negative outlook as to how the accuracy of multisensory integration may deteriorate across the lifespan, with older adults experiencing difficulties in speech perception and balance maintenance as a result of less modulated sensory processing. Whilst the findings of this thesis support the notion that older adults may experience difficulties in inhibiting task-irrelevant, distracting information, behavioural data from Chapters 5 and 6 indicate that speech perception and balance may be preserved despite this. Indeed, in Chapter 5, both younger and older adults produced a similar speech perception performance in noisy listening environments; interestingly, preliminary data indicate that older adults' speech perception actually improved when cognitive load increased due to a challenging balance task. In addition, in Chapter 6, younger and older adults appeared equivalent in their ability to attend to and retain task-relevant speech and suppress distracting speech. Here, we will explore potential reasons for the strong behavioural performance of the older adult participants in this thesis; the theories surrounding compensatory strategies that older adults could employ to preserve multisensory function, in spite of age-related declines in attentional control, are discussed.

7.4.2. Cognitive function in older adults: Cognitive Reserve theory

It is important to note that the older adult participants recruited in each chapter of this thesis appear to lie at the higher end of the cognitive ability spectrum. Whilst it was a prerequisite that all older adults had to be cognitively healthy (i.e. no evidence of mild cognitive decline, no history of psychological disorders), the observation that older adults produced a similar behavioural performance to younger adults in Chapters 5 and 6 of this thesis, in particular, suggest that they had stronger attentional control mechanisms than perhaps would be expected from this age group, based on previous literature (Hasher et al., 2007; Fabiani et al., 2006; Stothart & Kazanina, 2016).

One potential explanation for the individual differences in cognitive function between older adult participants could be found within the Cognitive Reserve theory of ageing (Stern et al., 2020; Oosterhuis et al., 2023). This theory postulates that lifestyle factors, such as educational, social, cognitive and physical activities, lead to the accumulation of "cognitive reserve", which increases cognitive flexibility by facilitating the use of alternative cognitive strategies, strengthening existing brain networks or recruiting different brain regions entirely (Stern et al., 2020; Oosterhuis et al., 2023). In the context of the current thesis, not only would older adults with high cognitive reserve evidence an improved ability to allocate attentional resources between two concurrent tasks (Chapter 5), but it may also enable the adoption of compensatory approaches to inhibit distracting speech in difficult listening environments, or stabilise postural control under challenging balance conditions (Chapters 5 and 6). Whilst the exact cognitive strategies enabled by cognitive reserve are still unknown, some researchers have suggested that cognitive reserve can counteract the age-related declines in attentional control and working memory resources (Oosterhuis et al., 2023; Lojo-Seoane et al., 2020). It follows that older adults with high cognitive reserve could exhibit enhanced processing speed, stronger inhibitory control and/or attentional processes, in order to improve more global cognitive abilities (Lojo-Seoane et al., 2020; Oosterhuis et al., 2023).

Although cognitive reserve was not measured in this thesis, there is strong evidence to suggest that the older adult participants within each chapter possessed high levels of cognitive reserve. For example, the majority of older adult participants were recruited via the Centre for Ageing Research at Lancaster University and the University of the Third Age – continued learning groups who are motivated to remain engaged in education, participate in research and learn more about the ageing process. Furthermore, Chapters 4 and 5 collected detailed information with regards to the physical activity levels of participants and their balance confidence – older adults' scores on each of these measures were not significantly different from (Chapter 4) or even greater than (Chapter 5) that of younger adults, highlighting the high physical fitness of the older adult samples. Taken together, it is reasonable to infer that the older adults in our sample would constitute people with high levels of cognitive reserve, despite not calculating a formal cognitive reserve score. This could be a key reason underlying any lack of behavioural differences between younger and older adults in each chapter of this thesis – even if age-related declines in the top-down modulation of sensory processing are present in the older adult samples, perhaps high cognitive reserve levels facilitated the use of compensatory strategies to preserve speech perception and balance maintenance performances.

7.4.3. Cognitive function in older adults: Motivational factors

Alongside cognitive reserve theories of ageing, a large section of discussion in the second half of this thesis surrounded how the high motivation levels of older adult participants may have impacted the findings, which could result in the portrayal of older adults having stronger-than-expected cognitive and physical abilities. Previous research has explored these potential biases present in ageing research along the lines of stereotype threat (Hess et al., 2003; Barber, 2017; Ryan & Campbell, 2021). Stereotype threat describes the phenomenon whereby previous preconceptions or exposure to a negative stereotype (e.g. weaker balance ability in older adults, worse hearing in older adults, problems with memory in older adults) can hinder performance these tasks, providing an inaccurate representation of an older adult's true abilities (Ryan & Campbell, 2021). Whilst stereotype threat is certainly a valid issue in neurocognitive studies into ageing and one which must be given due consideration in future research, this thesis may support an alternative stance. That is, highly motivated older adults may be aware that such negative ageing stereotypes exist, and subsequently engage increased cognitive resources during an experimental task to avoid confirming these stereotypes, resulting in a strong perceptual performance (Todd Maddox & Markman, 2012). Furthermore, aside from stereotype threat, intrinsic motivational differences are likely to exist between younger and older adults, in terms of affect and engagement in the task. For example, older adults are often interested in participating in research to understand more about their own brain health, and are motivated to produce a strong performance in order to maintain a positive view of their cognitive ability (Carstensen et al., 1999; Hess, 2014; Ryan & Campbell, 2021); this is not a major concern for younger adults, who may be motivated to participate to receive payment or course credit (Ryan & Campbell, 2021). As such, previous research suggests that older adults may possess a higher baseline motivation level compared to younger adults, resulting in a strong performance across experimental tasks.

Taken together, given that the older adults in each chapter of this thesis were highly motivated to participate in research studies, enthusiastic about their experience and eager to learn more about their cognitive health, perhaps any non-significant differences between younger and older adults were due to older adults being highly motivated to "prove" their speech perception and balance abilities (Ryan & Campbell, 2021). Whilst this is a positive indication of how older adults may approach the challenges associated with ageing, these motivational factors should be taken into account in future research when explaining why behavioural performance may be preserved in our ageing population, despite neural data suggesting age-related changes in cognitive control.

7.5. Thesis challenges and considerations for future research.

A limitation of this thesis, particularly with regards to the seemingly high cognitive and physical ability levels of the older adults in our samples, was a lack of composite measures of cognitive reserve throughout each study. Indeed, as discussed, many external lifestyle factors can contribute to the ability to utilise alternative cognitive strategies and flexibly allocate attentional resources across the lifespan (Reuter-Lorenz & Park, 2023). As such, details such as a participant's education levels, employment history and socialisation could have been collected (Oosterhuis et al., 2023), to calculate an overall cognitive reserve score which may have moderated the top-down attentional control exhibited by older adults. This would have allowed us to conclude, with more confidence, that any non-significant differences found between younger and older adults in this thesis may be due to the high cognitive functioning of our older adult samples. However, it is important to note that each older adult was screened for mild cognitive impairment and psychological conditions, so in this respect, we can be confident that our samples of older adults were 'healthy'. Furthermore, as mentioned previously, the high physical ability levels of the older adults in our samples, as well as the majority being involved in continued learning groups, suggests that the cognitive reserve levels of the older adults in this thesis were towards the higher end of the spectrum.

Following from this, a further limitation could be the fact that if the older adults in our sample were so highly-functioning, they may not be representative of the entire population as to how age-related changes in multisensory processing manifest across all older adults. For example, chapters in this thesis measured the pure-tone audiometry thresholds of participants, and no participants were deemed to have moderate-severe hearing loss. This was a valid eligibility criterion to implement in these studies as we were interested in measuring the cognitive mechanisms behind sensory processing; however, such restrictions on participation omit a large proportion of the population due to the frequency of hearing loss in this age group. It would be an interesting direction for future research to uncover how the attentional modulation of multisensory integration differs between older adults with normal hearing and older adults with hearing loss, particularly with regards to how task-irrelevant sensory information is inhibited and how this is reflected in alpha activity. Perhaps older adults with hearing loss would exhibit lower alpha activity; Alhanbali et al. (2022) implemented a digits-in-noise task and reported a negative correlation between pre-stimulus parietal alpha power and PTA thresholds, even when participants with hearing loss wore hearing aids. The researchers suggested that this negative relationship may reflect supra-threshold processing deficits in older adults with hearing loss (Alain et al., 2014), which are not restored through hearing aid amplification (Kortlang et al., 2016; Alhanbali et al., 2022). These investigations are important in building an inclusive account of how age-related changes in alpha activity occur in both normal hearing older adults and older adults with hearing loss, whose difficulties in tasks like speech perception may be exacerbated by the joint impact of supra-threshold processing deficits as well as age-related attentional declines.

Throughout this thesis, when physical ability and balance confidence were measured, there was either no difference between younger and older adults (Chapter 4), or older adults were actually more physically active than our younger adult sample (Chapter 5). Once again, this is highly unlikely to be representative of the entire population, who may experience physical frailty that comes from age-related muscle loss, medical conditions such as arthritis and joint pain, or a general lack of physical activity that comes with a sedentary lifestyle. In addition, it is important to note that there is a lack of ethnic and cultural diversity across ageing research, with the majority of older participants in this thesis belonging to WEIRD populations (White, Educated, Industrialised, Rich Democracies). Taken together, these factors may further limit the generalisability of findings with regards to how people from different facets of society may be impacted by age-related changes in multisensory integration (Rolison, 2024). Whilst recruitment in this thesis was limited by time and financial constraints, future research should ensure that the older adults recruited for each study represent each strata of the population, in terms of hearing health, cognitive function, physical ability, and additional measures of cognitive reserve (e.g. education, socio-economic status). This would allow for a more diverse and inclusive investigation of how the ageing process can affect the top-down modulation of audiovisual processing, how this is reflected in alpha activity, and the impact on older adults' performance in speech perception and balance tasks.

Finally, as mentioned at the beginning of this discussion, perhaps the non-significant differences in behavioural performance between younger and older adults in Chapters 5 and 6 of this thesis were due to the tasks implemented being insufficiently sensitive. Indeed, with such a highly-functioning older adult participant group, any impact that age-related changes in attentional control have on speech perception or balance performance may be subtle. Perhaps more challenging tasks were required, to adequately tax the cognitive resources of older adults and uncover such changes. For example, in the speech perception tasks in this thesis, implementing background speech that is semantically and phonetically similar to the target speech could have been a more sensitive paradigm – this increased informational masking is likely to have increased the difficulty of the tasks due to the increased distractibility of the task-irrelevant speech, for older adults in particular (Schneider & Daneman, 2007; Ben-David et al., 2012). Likewise, balance assessments used in clinical practice can often be insufficiently sensitive in detecting subtle changes in balance ability with increasing age (Balasubmaranian, 2015; Rockwood et al., 2008); not only is this a concern for clinicians in identifying whether an older adult is fall-prone, but it is an important consideration for future researchers aiming to study how balance maintenance may change as a function of healthy ageing. Crucially, whilst it is important that a task is sufficiently sensitive to detect differences in attentional control between younger and older adults, the cognitive resources expended by older adults may reach its maximum level if the task becomes too difficult, which can lead to declines in both motivation and performance (Reuter-Lorenz & Cappell, 2008). Careful consideration of the tasks implemented in neurocognitive paradigms investigating ageing is therefore key, to ensure that any existing behavioural differences between younger and older adults can be detected whilst simultaneously avoiding floor or ceiling effects.

7.6. Conclusion

To conclude, this thesis has demonstrated how age-related changes in the top-down modulation of multisensory processing can impact the perception and action of older adults. Through identifying alpha activity as a key underlying neural correlate of such changes, this research has provided novel contributions as to how younger and older adults may rely upon different cognitive strategies during everyday multisensory tasks like speech perception and balance maintenance. From this perspective, each chapter has emphasised the importance of understanding the real-world impact that age-related changes in multisensory integration may have on the quality of life of our increasingly ageing population, rendering these findings as being of theoretical and potentially clinical relevance. Earlier chapters in this thesis found that the weaker attentional control of older adults is likely to be a fundamental factor in their increased, less accurate multisensory integration. However, in later chapters, it was found that whilst these attentional deficits may exist, older adults appear be more robust to the negative effects than once thought. That is, when faced with complex stimuli such as speech, or under adverse balance conditions, heterogenous ageing trajectories may mean that some older adults are able to adopt compensatory approaches to preserve perceptual and motor performance. As such, this thesis also provided considerations for future neurocognitive research, casting light on the impact that these individual differences may have on an older adult's speech perception and balance performance, with cognitive reserve theories of ageing discussed throughout. Nevertheless, it is imperative that the findings of this thesis inspire further research into the functional role of alpha activity in attentional control, particularly with regards to the development of neurocognitive interventions which may improve the speech perception and balance abilities of older adults. Overall, furthering our understanding of the age-related changes in top-down attentional control, and how such changes may be reflected in neural oscillations within the alpha-band frequency and beyond, are crucial investigations in building a comprehensive account as to how multisensory processing is affected by healthy ageing.

References

Alain, C., Roye, A., & Salloum, C. (2014). Effects of age-related hearing loss and background noise on neuromagnetic activity from auditory cortex. *Frontiers in systems neuroscience*, *8*, 8.

Alhanbali, S., Munro, K. J., Dawes, P., Perugia, E., & Millman, R. E. (2022). Associations between pre-stimulus alpha power, hearing level and performance in a digits-in-noise task. *International journal of audiology*, *61*(3), 197-204.

Arlinger, S., Lunner, T., Lyxell, B., & Kathleen Pichora-Fuller, M. (2009). The emergence of cognitive hearing science. *Scandinavian journal of psychology*, *50*(5), 371-384.

Anderson, S., White-Schwoch, T., Parbery-Clark, A., & Kraus, N. (2013). Reversal of age-related neural timing delays with training. *Proceedings of the national academy of sciences*, *110*(11), 4357-4362.

Balasubramanian, C. K. (2015). The community balance and mobility scale alleviates the ceiling effects observed in the currently used gait and balance assessments for the community-dwelling older adults. *Journal of geriatric physical therapy*, *38*(2), 78-89.

Barban, F., Annicchiarico, R., Melideo, M., Federici, A., Lombardi, M. G., Giuli, S., ... & Caltagirone, C. (2017). Reducing fall risk with combined motor and cognitive training in elderly fallers. *Brain sciences*, *7*(2), 19.

Barber, S. J. (2017). An examination of age-based stereotype threat about cognitive decline: Implications for stereotype-threat research and theory development. *Perspectives on Psychological Science*, *12*(1), 62-90.

Barnett, S. M., & Ceci, S. J. (2002). When and where do we apply what we learn?: A taxonomy for far transfer. *Psychological bulletin*, *128*(4), 612.

Barutchu, A., Toohey, S., Shivdasani, M. N., Fifer, J. M., Crewther, S. G., Grayden, D. B., & Paolini, A. G. (2019). Multisensory perception and attention in school-age children. *Journal of experimental child psychology*, *180*, 141-155.

Bedard, G., & Barnett-Cowan, M. (2016). Impaired timing of audiovisual events in the elderly. *Experimental brain research*, *234*, 331-340.

Ben-David, B. M., Vania, Y. Y., & Schneider, B. A. (2012). Does it take older adults longer than younger adults to perceptually segregate a speech target from a background masker?. *Hearing research*, *290*(1-2), 55-63.

Bieber, R. E., & Gordon-Salant, S. (2021). Improving older adults’ understanding of challenging speech: Auditory training, rapid adaptation and perceptual learning. *Hearing Research*, *402*, 108054.

Burk, M. H., & Humes, L. E. (2007). Effects of training on speech recognition performance in noise using lexically hard words.

Burk, M. H., & Humes, L. E. (2008). Effects of long-term training on aided speech-recognition performance in noise in older adults.

Campbell, J., Nielsen, M., LaBrec, A., & Bean, C. (2020). Sensory inhibition is related to variable speech perception in noise in adults with normal hearing. *Journal of Speech, Language, and Hearing Research*, *63*(5), 1595-1607.

Carstensen, L. L., Isaacowitz, D. M., & Charles, S. T. (1999). Taking time seriously: A theory of socioemotional selectivity. *American psychologist*, *54*(3), 165.

De Dieuleveult, A. L., Siemonsma, P. C., Van Erp, J. B., & Brouwer, A. M. (2017). Effects of aging in multisensory integration: a systematic review. *Frontiers in aging neuroscience*, *9*, 80.

Deviterne, D., Gauchard, G. C., Jamet, M., Vançon, G., & Perrin, P. P. (2005). Added cognitive load through rotary auditory stimulation can improve the quality of postural control in the elderly. *Brain research bulletin*, *64*(6), 487-492.

Dey, A., & Sommers, M. S. (2015). Age-related differences in inhibitory control predict audiovisual speech perception. *Psychology and aging*, *30*(3), 634.

Dimitrijevic, A., Smith, M. L., Kadis, D. S., & Moore, D. R. (2017). Cortical alpha oscillations predict speech intelligibility. *Frontiers in human neuroscience*, *11*, 88.

Dimitrijevic, A., Smith, M. L., Kadis, D. S., & Moore, D. R. (2017). Cortical alpha oscillations predict speech intelligibility. *Frontiers in human neuroscience*, *11*, 88.

Donohue, S. E., Green, J. J., & Woldorff, M. G. (2015). The effects of attention on the temporal integration of multisensory stimuli. *Frontiers in Integrative Neuroscience*, *9*, 32.

Edwards, A. E., Guven, O., Furman, M. D., Arshad, Q., & Bronstein, A. M. (2018). Electroencephalographic correlates of continuous postural tasks of increasing difficulty. *Neuroscience*, *395*, 35-48.

Fabiani, M., Low, K. A., Wee, E., Sable, J. J., & Gratton, G. (2006). Reduced suppression or labile memory? Mechanisms of inefficient filtering of irrelevant information in older adults. *Journal of cognitive neuroscience*, *18*(4), 637-650.

Gazzaley, A., Clapp, W., Kelley, J., McEvoy, K., Knight, R. T., & D'Esposito, M. (2008). Age-related top-down suppression deficit in the early stages of cortical visual memory processing. *Proceedings of the National Academy of Sciences*, *105*(35), 13122-13126.

Getzmann, S., Golob, E. J., & Wascher, E. (2016). Focused and divided attention in a simulated cocktail-party situation: ERP evidence from younger and older adults. *Neurobiology of aging*, *41*, 138-149.

Getzmann, S., Jasny, J., & Falkenstein, M. (2017). Switching of auditory attention in “cocktail-party” listening: ERP evidence of cueing effects in younger and older adults. *Brain and cognition*, *111*, 1-12.

Getzmann, S., Wascher, E., & Falkenstein, M. (2015). What does successful speech-in-noise perception in aging depend on? Electrophysiological correlates of high and low performance in older adults. *Neuropsychologia*, *70*, 43-57.

Gordon-Salant, S., & Cole, S. S. (2016). Effects of age and working memory capacity on speech recognition performance in noise among listeners with normal hearing. *Ear and hearing*, *37*(5), 593-602.

Hasher, L., Lustig, C., & Zacks, R. T. (2007). Inhibitory mechanisms and the control of attention. *Variation in working memory*, *19*, 227-249.

Hasher, L., Stoltzfus, E. R., Zacks, R. T., & Rypma, B. (1991). Age and inhibition. *Journal of experimental psychology: Learning, memory, and cognition*, *17*(1), 163.

Hernández, B., Setti, A., Kenny, R. A., & Newell, F. N. (2019). Individual differences in ageing, cognitive status, and sex on susceptibility to the sound-induced flash illusion: A large-scale study. *Psychology and Aging*, *34*(7), 978.

Herrmann, B., Maess, B., Henry, M. J., Obleser, J., & Johnsrude, I. S. (2022). Age-related changes in the neural mechanics of dynamic auditory attention in time. *bioRxiv*, 2022-04.

Hess, T. M. (2014). Selective engagement of cognitive resources: Motivational influences on older adults' cognitive functioning. *Perspectives on Psychological Science*, *9*(4), 388-407.

Hess, T. M., Auman, C., Colcombe, S. J., & Rahhal, T. A. (2003). The impact of stereotype threat on age differences in memory performance. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *58*(1), P3-P11.

Hirst, R. J., Setti, A., Kenny, R. A., & Newell, F. N. (2019). Age-related sensory decline mediates the Sound-Induced Flash Illusion: Evidence for reliability weighting models of multisensory perception. *Scientific Reports*, *9*(1), 19347.

Hugenschmidt, C. E., Mozolic, J. L., & Laurienti, P. J. (2009). Suppression of multisensory integration by modality-specific attention in aging. *Neuroreport*, *20*(4), 349-353.

Jensen, O., & Mazaheri, A. (2010). Shaping functional architecture by oscillatory alpha activity: gating by inhibition. *Frontiers in human neuroscience*, *4*, 186.

Kortlang, S., Mauermann, M., & Ewert, S. D. (2016). Suprathreshold auditory processing deficits in noise: Effects of hearing loss and age. *Hearing research*, *331*, 27-40.

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1993). Attentional demands for static and dynamic equilibrium. *Experimental brain research*, *97*, 139-144.

Lojo-Seoane, C., Facal, D., Guàrdia-Olmos, J., Pereiro, A. X., Campos-Magdaleno, M., Mallo, S. C., & Juncos-Rabadán, O. (2020). Cognitive reserve and working memory in cognitive performance of adults with subjective cognitive complaints: longitudinal structural equation modeling. *International psychogeriatrics*, *32*(4), 515-524.

Lustig, C., Hasher, L., & Zacks, R. T. (2007). Inhibitory deficit theory: recent developments in a" new view".

Merriman, N. A., Whyatt, C., Setti, A., Craig, C., & Newell, F. N. (2015). Successful balance training is associated with improved multisensory function in fall-prone older adults. *Computers in human behavior*, *45*, 192-203.

Mozolic, J. L., Hugenschmidt, C. E., Peiffer, A. M., & Laurienti, P. J. (2008). Modality-specific selective attention attenuates multisensory integration. *Experimental brain research*, *184*, 39-52.

Neumann, E., & DeSchepper, B. G. (1991). Costs and benefits of target activation and distractor inhibition in selective attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *17*(6), 1136.

Oosterhuis, E. J., Slade, K., May, P. J. C., & Nuttall, H. E. (2023). Toward an understanding of healthy cognitive aging: the importance of lifestyle in cognitive reserve and the scaffolding theory of aging and cognition. *The Journals of Gerontology: Series B*, *78*(5), 777-788.

Oosterhuis, E. J., Slade, K., Smith, E., May, P. J., & Nuttall, H. E. (2023). Getting the brain into gear: An online study investigating cognitive reserve and word-finding abilities in healthy ageing. *Plos one*, *18*(4), e0280566.

Ozdemir, R. A., Contreras-Vidal, J. L., & Paloski, W. H. (2018). Cortical control of upright stance in elderly. *Mechanisms of ageing and development*, *169*, 19-31.

Ozdemir, R. A., Contreras-Vidal, J. L., Lee, B. C., & Paloski, W. H. (2016). Cortical activity modulations underlying age-related performance differences during posture–cognition dual tasking. *Experimental brain research*, *234*, 3321-3334.

Parry, S. W., Frearson, R., Steen, N., Newton, J. L., Tryambake, P., & Kenny, R. A. (2008). Evidence-based algorithms and the management of falls and syncope presenting to acute medical services. *Clinical medicine*, *8*(2), 157-162.

Peelle, J. E., Troiani, V., Wingfield, A., & Grossman, M. (2010). Neural processing during older adults' comprehension of spoken sentences: age differences in resource allocation and connectivity. *Cerebral cortex*, *20*(4), 773-782.

Perceval, G., Martin, A. K., Copland, D. A., Laine, M., & Meinzer, M. (2020). Multisession transcranial direct current stimulation facilitates verbal learning and memory consolidation in young and older adults. *Brain and Language*, *205*, 104788.

Pichora-Fuller, M. K., Alain, C., & Schneider, B. A. (2017). Older adults at the cocktail party. *The auditory system at the cocktail party*, 227-259.

Powers, A. R., Hevey, M. A., & Wallace, M. T. (2012). Neural correlates of multisensory perceptual learning. *Journal of Neuroscience*, *32*(18), 6263-6274.

Reuter-Lorenz, P. A., & Park, D. C. (2014). How does it STAC up? Revisiting the scaffolding theory of aging and cognition. *Neuropsychology review*, *24*, 355-370.

Reuter-Lorenz, P. A., & Park, D. C. (2023). Cognitive aging and the life course: A new look at the scaffolding theory. *Current Opinion in Psychology*, 101781.

Rockwood, K., Rockwood, M. R., Andrew, M. K., & Mitnitski, A. (2008). Reliability of the hierarchical assessment of balance and mobility in frail older adults. *Journal of the American Geriatrics Society*, *56*(7), 1213-1217.

Rolison, J. J. (2024). Diversity in the study of aging and lifespan development. *Current Opinion in Psychology*, 101802.

Ryan, A. D., & Campbell, K. L. (2021). The ironic effect of older adults' increased task motivation: Implications for neurocognitive aging. *Psychonomic Bulletin & Review*, *28*(6), 1743-1754.

Schneider, B. A., Li, L., & Daneman, M. (2007). How competing speech interferes with speech comprehension in everyday listening situations. *Journal of the American Academy of Audiology*, *18*(07), 559-572.

Schurman, J., Brungart, D., & Gordon-Salant, S. (2014). Effects of masker type, sentence context, and listener age on speech recognition performance in 1-back listening tasks. *The Journal of the Acoustical Society of America*, *136*(6), 3337-3349.

Setti, A., Hernández, B., Hirst, R. J., Donoghue, O. A., Kenny, R. A., & Newell, F. N. (2023). Susceptibility to the sound-induced flash illusion is associated with gait speed in a large sample of middle-aged and older adults. *Experimental Gerontology*, *174*, 112113.

Shaw, E. P., Rietschel, J. C., Hendershot, B. D., Pruziner, A. L., Miller, M. W., Hatfield, B. D., & Gentili, R. J. (2018). Measurement of attentional reserve and mental effort for cognitive workload assessment under various task demands during dual-task walking. *Biological psychology*, *134*, 39-51.

Smith-Ray, R. L., Hughes, S. L., Prohaska, T. R., Little, D. M., Jurivich, D. A., & Hedeker, D. (2015). Impact of cognitive training on balance and gait in older adults. *Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *70*(3), 357-366.

Sobral, M., Guiomar, R., Martins, V., & Ganho-Ávila, A. (2022). Home-based transcranial direct current stimulation in dual active treatments for symptoms of depression and anxiety: a case series. *Frontiers in Psychiatry*, *13*, 947435.

Stapleton, J., Setti, A., Doheny, E. P., Kenny, R. A., & Newell, F. N. (2014). A standing posture is associated with increased susceptibility to the sound-induced flash illusion in fall-prone older adults. *Experimental brain research*, *232*, 423-434.

Stern, Y., Arenaza-Urquijo, E. M., Bartrés-Faz, D., Belleville, S., Cantilon, M., Chetelat, G., ... & Reserve, Resilience and Protective Factors PIA Empirical Definitions and Conceptual Frameworks Workgroup. (2020). Whitepaper: Defining and investigating cognitive reserve, brain reserve, and brain maintenance. *Alzheimer's & Dementia*, *16*(9), 1305-1311.

Stothart, G., & Kazanina, N. (2016). Auditory perception in the aging brain: the role of inhibition and facilitation in early processing. *Neurobiology of aging*, *47*, 23-34.

Talsma, D., Kok, A., & Ridderinkhof, K. R. (2006). Selective attention to spatial and non-spatial visual stimuli is affected differentially by age: effects on event-related brain potentials and performance data. *International Journal of Psychophysiology*, *62*(2), 249-261.

Talsma, D., Senkowski, D., Soto-Faraco, S., & Woldorff, M. G. (2010). The multifaceted interplay between attention and multisensory integration. *Trends in cognitive sciences*, *14*(9), 400-410.

Tipper, S. P. (1991). Less attentional selectivity as a result of declining inhibition in older adults. *Bulletin of the Psychonomic Society*, *29*(1), 45-47.

Tipper, S. P., & Cranston, M. (1985). Selective attention and priming: Inhibitory and facilitatory effects of ignored primes. *The Quarterly Journal of Experimental Psychology*, *37*(4), 591-611.

Todd Maddox, W., & Markman, A. B. (2010). The motivation–cognition interface in learning and decision making. *Current Directions in Psychological Science*, *19*(2), 106-110.

van Het Reve, E., & de Bruin, E. D. (2014). Strength-balance supplemented with computerized cognitive training to improve dual task gait and divided attention in older adults: a multicenter randomized-controlled trial. *BMC geriatrics*, *14*, 1-15.

Whitton, J. P., Hancock, K. E., & Polley, D. B. (2014). Immersive audiomotor game play enhances neural and perceptual salience of weak signals in noise. *Proceedings of the National Academy of Sciences*, *111*(25), E2606-E2615.

Whitton, J. P., Hancock, K. E., & Polley, D. B. (2014). Immersive audiomotor game play enhances neural and perceptual salience of weak signals in noise. *Proceedings of the National Academy of Sciences*, *111*(25), E2606-E2615.

Woodham, R. D., Selvaraj, S., Lajmi, N., Hobday, H., Sheehan, G., Ghazi-Noori, A. R., ... & Fu, C. H. (2023). Home-based transcranial direct current stimulation RCT in major depression. *medRxiv*, 2023-11.

Wöstmann, M., Herrmann, B., Wilsch, A., & Obleser, J. (2015). Neural alpha dynamics in younger and older listeners reflect acoustic challenges and predictive benefits. *Journal of Neuroscience*, *35*(4), 1458-1467.

Wöstmann, M., Lim, S. J., & Obleser, J. (2017). The human neural alpha response to speech is a proxy of attentional control. *Cerebral cortex*, *27*(6), 3307-3317.

Zelinski, E. M. (2009). Far transfer in cognitive training of older adults. *Restorative neurology and neuroscience*, *27*(5), 455-471.

Zhang, S., Xu, W., Zhu, Y., Tian, E., & Kong, W. (2020). Impaired multisensory integration predisposes the elderly people to fall: a systematic review. *Frontiers in neuroscience*, *14*, 411.

Appendices

Appendix A – Speech, Spatial and Quality of Hearing (SSQ) Questionnaire

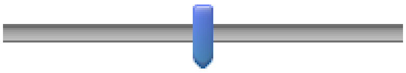
The following questions will ask you about aspects of your hearing ability, hearing experience and listening in different situations.

For each question, move the blue marker along the slider and place it anywhere on the scale from 0 to 10.

Putting the blue marker at 10 means that you would be perfectly able to do or experience what is described in the question. Putting the blue marker at 0 means that you would be unable to do or experience what is described.

As an example, the first question asks about following a conversation with someone whilst the TV is on at the same time. If you are well able to do this, put the blue marker at the right-hand end of the scale, at number 10. If you could follow about half the conversation in this situation, put the blue marker around half-way along the scale, and so on.

Q1 You are talking with one other person and there is a TV on in the same room. Without turning the TV down, can you follow what the person you're talking to says?

	Not at all Perfectly 0 1 2 3 4 5 6 7 8 9 10
()	

Q2 You are listening to someone talking to you, while at the same time trying to follow the news on TV. Can you follow what both people are saying?

Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

()

Q3 You are in conversation with one person in a room where there are many other people talking. Can you follow what the person you are talking to is saying?

Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

()

Q4 You are in a group of about five people in a busy restaurant. You can see everyone else in the group. Can you follow the conversation?

Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

()

Q5 You are with a group and the conversation switches from one person to another. Can you easily follow the conversation without missing the start of what each new speaker is saying?

Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

()

Q6 You are outside. A dog barks loudly. Can you tell immediately where it is, without having to look?

Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

()

Q7 Can you tell how far away a bus or a truck is, from the sound?

Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

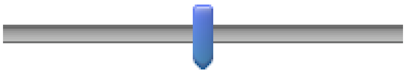
()

Q8 Can you tell from the sound whether a bus or truck is coming towards you or going away?

Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

()



Q9 When you hear more than one sound at a time, do you have the impression that it seems like a single jumbled sound?

Jumbled Not jumbled

0 1 2 3 4 5 6 7 8 9 10

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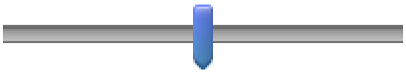
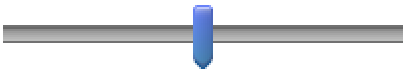


Q10 When you listen to music, can you make out which instruments are playing?

Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

()

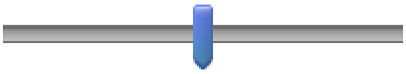


Q11 Do everyday sounds that you can hear easily seem clear to you (not blurred)?

Not at all Perfectly

0 1 2 3 4 5 6 7 8 9 10

()

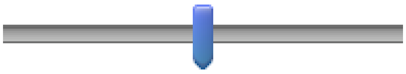


Q12 Do you have to concentrate very much when listening to someone or something?

Concentrate hard No need to concentrate

0 1 2 3 4 5 6 7 8 9 10

()



Appendix B – Informant Questionnaire on Cognitive Decline in the Elderly (IQ-CODE) pre-screening questionnaire

Below are some situations where you have to use your memory or intelligence. Please indicate whether you have improved, stayed the same or got worse in that situation **compared to 10** years.

Q1 Compared to 10 years ago, how are you at remembering things about family and friends e.g. occupations, birthdays, addresses?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q2 Compared to 10 years ago, how are you at remembering things that have happened recently?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q3 Compared to 10 years ago, how are you at recalling conversations a few days later?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q4 Compared to 10 years ago, how are you at remembering your address and telephone number?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q5 Compared to 10 years ago, how are you at remembering what day and month it is?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q6 Compared to 10 years ago, how are you at remembering where things are usually kept?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q7 Compared to 10 years ago, how are you at remembering where to find things which have been put in a different place from usual?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q8 Compared to 10 years ago, how are you at knowing how to work familiar machines around the house?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q9 Compared to 10 years ago, how are you at learning to use a new gadget or machine around the house?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q10 Compared to 10 years ago, how are you at learning new things in general?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q11 Compared to 10 years ago, how are you at following a story in a book or on TV?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q12 Compared to 10 years ago, how are you at making decisions on everyday matters?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q13 Compared to 10 years ago, how are you at handling money for shopping?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q14 Compared to 10 years ago, how are you at handling financial matters e.g. the pension, dealing with the bank?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q15 Compared to 10 years ago, how are you at handling other everyday arithmetic problems e.g. knowing how much food to buy, knowing how long between visits from family or friends?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Q16 Compared to 10 years ago, how are you at using your intelligence to understand what is going on and to reason things through?

○ Much improved (1)

○ A bit improved (2)

○ Not much change (3)

○ A bit worse (4)

○ Much worse (5)

Appendix C – Activities-Specific Balance Confidence scale (ABC)

For each of the following activities, please indicate your level of confidence in doing the activity, without losing your balance or becoming unsteady.

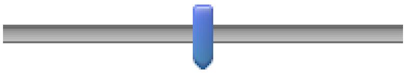
To do so, choose one of the percentage points on the scale from 0 (no confidence) to 10 (complete confidence)

If you do not currently do the activity in question, try and imagine how confident you would be if you had to do the activity.

Q2 Walk around the house?

No confidence Complete confidence

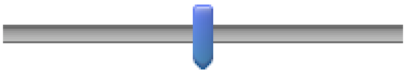
0 10 20 30 40 50 60 70 80 90 100

()	

Q3 Walk up or down stairs?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

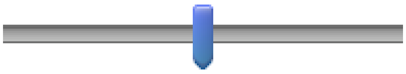
()	

Q4 Bend over and pick up a slipper from the front of a closet floor?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

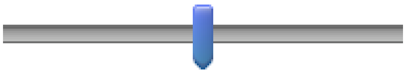


Q5 Reach for a small can off a shelf at eye level?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

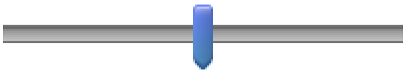


Q6 Stand on your tiptoes and reach for something above your head?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()



Q7 Stand on a chair and reach for something?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

Q8 Sweep the floor?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

Q9 Walk outside the house to a car parked in the driveway?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

Q10 Get into or out of a car?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

Q11 Walk across a car park to a shop?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

Q12 Walk up or down a ramp?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

Q13 Walk in a crowded shop where people rapidly walk past you?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

Q14 Are bumped into by people as you walk through the shop?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

Q15 Step onto or off an escalator while you are holding onto a railing?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

Q16 Step onto or off an escalator while holding onto parcels such that you cannot hold onto the railing?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

Q17 Walk outside on icy pavements?

No confidence Complete confidence

0 10 20 30 40 50 60 70 80 90 100

()

Appendix D – Rapid Assessment of Physical Activity (RAPA) questionnaire

Physical Activities are activities where you move and increase your heart rate above its resting rate, whether you do them for pleasure, work, or transportation.

The following questions ask about the amount and intensity of physical activity you usually do. The intensity of the activity is related to the amount of energy you use to do these activities.

Light Activities:

- your heart beats slightly faster than normal
- you can talk and sing

Moderate Activities:

- your heart beats faster than normal
- you can talk but not sing

Vigorous Activities

- your heart rate increases a lot
- you can't talk or your talking is broken up by large breaths

How physically active are you? Please check either "Yes" or "No" on each line whether you think that the statement accurately describes you.

Q1 I rarely or never do any physical activities.

○ Yes

○ No

Q2 I do some light or moderate physical activities, but not every week.

○ Yes

○ No

Q3 I do some light physical activity every week.

○ Yes

○ No

Q4 I do moderate physical activities every week, but less than 30 minutes a day or 5 days a week.

○ Yes

○ No

Q5 I do vigorous physical activities every week, but less than 20 minutes a day or 3 days a week.

○ Yes

○ No

Q6 I do 30 minutes or more a day of moderate physical activities, 5 or more days a week.

○ Yes

○ No

Q7 I do 20 minutes or more a day of vigorous physical activities, 3 or more days a week.

○ Yes

○ No

Q8 I do activities to increase muscle strength, such as lifting weights or calisthenics, once a week or more.

○ Yes

○ No

Q9 I do activities to improve flexibility, such as stretching or yoga, once a week or more.

○ Yes

○ No