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Falls and Multisensory Processing: Exploring Multisensory Perception as a Potential Rehabilitation Avenue for Fall-prone Older Adults

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Publication-based thesis submitted for the degree of PhD by Research

Submission date: September 2022

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List of Acronyms

2-AFC: 2-Alternate Forced Choice task

2-IFC: 2-Interval Forced Choice task

ANOVA: Analysis of Variance

AV: Audio-Visual

BOLD: Blood Oxygen Level Dependent

CSO: Central Statistics Office

EEG: Electro-encephalography

ERP: Event Related Potential

fMRI: Functional Magnetic Resonance Imaging

HSE: Health Service Executive

IPAQ: International Physical Activity Questionnaire

MCI: Mild Cognitive Impairment

MEG: Magnetoencephalography

MINORS: Methodological Index for Non-Randomised Studies

MSI: Multisensory Integration

P300: P3 event related potential component

PPI: Public and Patient Involvement

PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses

PROSPERO: International Prospective Register of Systematic Reviews pSTS: Posterior Temporal Sulcus

RCT: Randomised Control Trial

ROB-2: Risk of Bias tool 2.0

SiFI: Sound-induced Flash Illusion

SJ: Simultaneity Judgement

SMMSE: Standardised Mini-Mental State Examination

SOA: Stimulus Onset Asynchrony

SOM: Somatosensory ratio

STS: Superior Temporal Sulcus

TBW: Temporal Binding Window

TFR: Time Frequency Analysis

TILDA: The Irish Longitudinal Study on Ageing

TMS: Transcranial Magnetic Stimulation

TOJ: Temporal Order Judgement

TUG: Timed Up and Go task

TWI: Temporal Window of Integration

UN: United Nations

UNDESA: United Nations Department of Economic and Social Affairs

WOS: Web Of Science

Declaration of Academic Honesty

This is to certify that the work I am submitting is my own and has not been submitted for another degree, either at University College Cork or elsewhere. All external references and sources are clearly acknowledged and identified within the contents. I have read and understood the regulations of University College Cork concerning plagiarism and intellectual property.

Signed: ____________________________

Jessica O'Brien

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Abstract

Population ageing and global goals of striving for healthy ageing for our older citizens coincides with rapid developments in multisensory research. Research demonstrating older adults rely more on multisensory inputs compared to younger individuals, as well as mounting evidence linking multisensory processing abilities to cognitive and functional ageing present exciting possibilities for novel intervention and prevention avenues for healthy ageing. This thesis focuses on making initial steps to bridge the gap in translating multisensory research into real world outcomes.

Firstly, we present the first systematic review of the evidence base for training multisensory integration. We found 26 studies which collectively show multisensory integration can be trained (i.e., temporal acuity or task performance improved) in younger and older adults. Two training approaches were identified in the literature; psychophysics-based perceptual training and exercise/movement-based training. The review highlighted gaps in our knowledge of training multisensory processing, including issues of generalisability and the dearth of training studies with older individuals. An experimental study was conducted that took a perceptual training paradigm previously successful with young adults and replicated this with a sample of community-dwelling older adults, finding training had benefits for an older population also.

Next, we sought to further explore the link between multisensory temporal integration and functional ageing, focusing on the case of falls in older adults. Based on the systematic review's finding that few training studies included clinical outcome measurements and that no study has explored the effect of existing falls interventions on multisensory processing, a study protocol was devised to address these gaps in the literature. Pilot data are presented for this experimental study focused on exploring

the impact of a programme of Physiotherapist-led exercise on behavioural and neurophysiological measures of multisensory integration in older fallers. This work highlighted a number of methodological barriers to conducting Electroencephalography research with this population, including data contamination and selection of appropriate outcome measurements. A complementary qualitative investigation garnered insights from older fallers who participated in the experiment and aimed to explore their views of being a research participant. This work highlighted older fallers' motivations for and barriers to research participation, as well as providing meaningful insights into their conceptualisation of their falls.

This thesis as a whole provides novel experimental data and qualitative insights, contributing to aspects underexplored in the field of multisensory research and ageing. The work has implications for future research aiming to fulfil the clinical-translational value of multisensory and ageing research, specifically in relation to interventions targeting multisensory processing and research involving fall-prone older adults.

Chapter One: General Introduction

Our population is ageing and ageing quickly, a pattern seen the world over. Our world had 1 billion adults aged 60+ in 2019, with a projected rise to 2.1 billion by the year 2050. In Europe, those aged 60+ represent the largest percentage of the population at 24% or 177 million people (UNDESA, 2015). In Ireland, the population aged 60+ was 696,300 in 2019, and is projected to double to over 1.5 million by 2051 (CSO, 2019).

Population ageing represents both a challenge and an opportunity. The current decade (2021 – 2030) has been marked the UN Decade of Healthy Ageing, with a plan for “concerted, catalytic and collaborative action to improve the lives of older people, their families and the communities in which they live” (World Health Organisation, 2020). The challenge for individuals experiencing advancing age, their families, and the societies they belong to, is how to preserve quality of life and independence as the years progress. In effect, how to age successfully. Advancing age brings with it a plethora of challenges, including threats to cognitive functioning, physical health, functional ability as well as social and emotional wellbeing.

Research can contribute to support countries and global societies to in turn support their older populations to age well. The concept of successful ageing has endured in gerontology and ageing research circles (Wahl et al., 2016), capturing the goals of reducing risk of disease and disability, preserving cognitive and physical functioning and being actively engaged with life (Rowe & Kahn, 1997). Recent decades have seen advances in knowledge around existing issues of ageing as well as breakthroughs into new factors which may affect one’s success in ageing.

Multisensory integration (MSI) is a perceptual process which is fast emerging as an important factor in healthy ageing, with research linking it to both cognitive and functional ageing. Living in a multisensory world, our brains are designed to integrate inputs from different senses to form a singular coherent percept (Freiherr et al., 2013; Stein & Meredith, 1990). Each moment of our lives we interact with a multisensory environment, our brains are tasked with collating the barrage of multisensory inputs we receive, whether they are auditory (e.g., car horns, mobile phone sounds, others' conversation), visual (e.g., traffic light signals, oncoming cars or pedestrians etc.) or spatial, somatosensory, tactile and so forth. In multisensory research, the classic example of someone speaking to you highlights the brain's integration task. You are presented with both visual information (e.g., the person's lips moving, gestures, facial expressions) as well as auditory information (e.g., the sounds they speak, the inflection of tone). If we think about this scenario, we know that access to both sources of information improves our ability to understand the other person's message, taking away either the visual or auditory elements of speech affects our processing of that information. Efficient multisensory integration underlies our ability not just for speech perception, but perception more broadly, cognitive processing and action control (Freiherr et al., 2013; Stein & Meredith, 1990), which in turn affect one's functional ability, including mobility and successful completion of the activities of daily life (Chiba et al., 2016; De Dieuleveult et al., 2017). Thus we can see the foundational role of a basic sensory process such as multisensory integration in our ability to live independently, a crucial measure of functional performance and successful ageing for our older citizens.

Multisensory integration changes over the life course, with a multisensory 'benefit' observed in later life, whereby older adults exhibit greater integration of multisensory stimuli across longer temporal intervals compared to younger cohorts (see De Dieuleveult et al., 2017). This greater integration is thought to reflect a compensatory mechanism for ageing, to account for diminished unisensory processing, degraded sensory information and age-related changes in cognitive processing (Freiherr et al., 2013; Hairston et al., 2003). This theory follows the principle of inverse effectiveness, such that enhancements in multisensory integration are compensating for potentially less reliable unisensory processing. For example, experimental work by Elliott and colleagues (2011) presents evidence that multisensory temporal integration (i.e., timing aspect of binding sensory inputs together) in older adults may compensate for impairments in coordinating actions, with improved ability to synchronise actions in multisensory versus unisensory conditions. The theories seeking to explain multisensory enhancements in older adults are outlined in the systematic review in the next chapter (Chapter Two).

Although there are clear benefits of enhanced integration, research points to the likely adverse consequences of this greater (or 'less precise') integration, with links to cognitive and functional decline in older people. In the context of cognitive ageing, less precise multisensory integration has been linked to mild cognitive impairment (Chan et al., 2015), poorer global cognition (Hernández et al., 2019) and poorer performance across a range of cognitive tasks (Hirst et al., 2022). In terms of functional ability in old age, multisensory integration has been associated with balance (Mahoney et al., 2019), gait (Mahoney & Verghese, 2018) and falls (Setti et al., 2011; Stapleton et al., 2014). Multisensory integration and its link to falls has seen particular research focus, with a recent review concluding impaired multisensory integration could predispose older adults to fall (Zhang et al., 2020). Extended or less precise multisensory integration is associated with impaired perceived timing of falls (Lupo & Barnett-Cowan, 2017, 2018) and higher number of falls across a 10 year period (O'Dowd et al., 2022). Falls in older adults represents an aspect where multisensory integration may have clinical utility, considering the gap in our knowledge around the potential link between this perceptual function and clinical outcomes (see Mahoney & Barnett-Cowan, 2019).

The temporal aspect of multisensory integration has seen particular attention due to growing evidence of its implications for functional ability in ageing (see Paraskevoudi et al., 2018). Previous research has documented age-related changes to unisensory temporal processing, with reduced temporal perception observed for both auditory and visual processing, for example impaired ability to detect visual gaps and impairments in motion perception (see review by Brooks et al., 2018). This is thought to reflect physiological changes in the ageing brain and the associated decline in unisensory processing often observed in ageing (e.g., reduced vision and hearing acuity in older adults). It is intuitive then that audio-visual temporal integration is also impacted by the ageing process. Indeed older adults exhibit difficulties in discriminating temporal order of multiple sensory inputs (Bedard & Barnett-Cowan, 2016; de Boer-Schellekens & Vroomen, 2014; Setti et al., 2011), and show increased susceptibility to audio-visual illusions (Hernández et al., 2019; McGovern et al., 2014; Setti et al., 2011). The concept of the Temporal Binding Window (TBW) is used to explain these findings in the literature. The TBW refers to the time window during which temporally synchronous sensory inputs will be bound together or 'integrated', a process which allows for the variation in speeds of sensory information arriving to the central nervous system (e.g., light travelling faster than sound; Colonius & Diederich, 2004). The TBW follows a U-shaped developmental pattern over the lifespan, with a larger TBW (i.e., stimuli more temporally distant are being integrated) observed in children and older adults, with narrowest integration closest to true simultaneity observed in the intervening adulthood years (Noel et al., 2016; Stevenson et al., 2018). There is evidence that this enlarged TBW in older adults may compromise general cognitive skills (Chan et al., 2015), language ability (Virsu et al., 2003) and balance maintenance (Zhang et al., 2020).

With the exponential growth of multisensory research in recent decades, some aspects have been left under researched and many questions remain. This PhD thesis aims to further the growing evidence for the role of multisensory integration in falls amongst our older population. This thesis seeks to understand whether multisensory integration is malleable in older adults and to further our understanding of the relationship between falls, potentially opening up the possibility for novel rehabilitation and prevention avenues. The work presented here aims to build on the emerging literature linking impaired multisensory perception to functional abilities and mobility, and, related to that, falls. If multisensory perceptual deficits in older people contribute to falls, this represents an exciting avenue for prevention and intervention of a major public health challenge for our healthcare systems. Western Europe is a region of the world with one of the highest rates of falls-related injury and mortality (Haagsma et al., 2016), with falls being a leading cause of hospitalisation and loss of independent living (Tinetti & Williams, 1997). Falling amongst our older population represents a distinct threat to successful ageing. Exploring the link between falls and multisensory processing is paramount, with considerable applied potential for healthcare and society. Specifically, there is value in exploring the potential role of physical exercise and movement in ameliorating multisensory processing deficits, with the aim of reducing falls. It is plausible that the association between multisensory processing and physical movement is a two-way relationship; we know multisensory processing is fundamental to movement (Stein, 2012) and so, physical exercise may represent a means to use and possibly, improve multisensory processing abilities in older individuals.

Chapter 2 details a systematic review of the literature on training multisensory integration in adults. With the advent of methodological means to quantify an individual's multisensory integration abilities (see Colonius & Diederich, 2020; Stevenson, Ghose, et al., 2014), the literature on multisensory perception has expanded to see interventions and training protocols targeting this perceptual function. In Chapter 2, we review this literature to explore what the evidence to date says regarding the trainability of multisensory integration. This is an important step towards exploring the clinical utility of multisensory integration for groups of society that exhibit impairments in multisensory processing, including, potentially, older fallers. The review looked at well-established types of perceptual training, such as psychophysics protocols as well as alternative training options emerging in the literature; training using movement or physical activity. The review identifies promising avenues for further research (e.g., physical exercise paradigms for training multisensory processing) and also indicates a number of gaps in the current training literature which could be addressed in future studies (e.g., mixed results in terms of transfer of training benefits, lack of clinical outcome measurements for correlation purposes).

Chapter 3 contains Study One 'Audio-visual Training in Older Adults: 2-Interval-Forced-Choice Task Improves Performance' (O'Brien, Chan & Setti, 2020). This study expanded on previous research finding audio-visual temporal discrimination training is successful with young adults (Powers et al., 2009; Powers et al., 2016; Theves et al., 2020), by testing older adults with this training paradigm over 3 days. Perceptual training studies targeting multisensory integration for improvement have focused primarily on young adults, with limited research conducted with older adult populations. Given the potential applied value of training for older adults who exhibit problems with multisensory integration, Study One tested whether temporal discrimination training was also effective for older adults. A control group of young adults were tested for comparison purposes and to replicate previous findings, which document different training durations, 5 day (Powers et al., 2009; Powers et al., 2016) or 1 day training (Theves et al., 2020). Study One demonstrates that 3 days of Simultaneity Judgement training using the 2-IFC paradigm with feedback is successful in training older and younger adults' performance on the 2-IFC task. The study also provides evidence that 2-IFC training does not generalise to performance on another audio-visual task, the Sound-induced Flash Illusion (SiFI) for either age group. This original research study has been published in Frontiers in Neuroscience.

After showing that multisensory perception is trainable in older adults (at least within task), Chapter 4 builds on the knowledge gained from the systematic review of the evidence base for training multisensory integration (Chapter 2). The review provided promising evidence that multisensory integration is modifiable through classical perceptual training paradigms (i.e., psychophysics tasks with in-task feedback), for both young and older adults. Yet, the psychophysics training studies presented mixed and at times conflicting results, precluding knowledge around what the optimal type of training would look like and the generalisability of training benefits. The review also highlighted promising new avenues for training, in particular physical activity or movement-based training approaches, complementing recent evidence of links between physical activity and multisensory processing in older people (Mahoney et al., 2015; O'Brien et al., 2017). The field of multisensory integration is tasked with exploring and realising the applied and clinical value of the field (see Barnett-Cowan, 2018; Mahoney & Barnett-Cowan, 2019). Considering the very limited success of cognitive training on real world clinical outcomes, the call for an ecological approach to training may prove insightful for the growing field of perceptual training (see Moreau & Conway, 2014). To date, no study has explored the impact of existing public healthcare programmes for falls on multisensory perception. This represents a dearth in the literature, given the potential value of ecological training for maximising clinical and functional outcomes post-training (Moreau & Conway, 2014). Chapter 4 presents a study aimed at exploring the impact of a standard falls programme on older fallers' multisensory integration and functional abilities (i.e., balance, falls risk). This experimental study also utilised Electroencephalography (EEG) to measure electrical brain activity during a multisensory integration task to explore training effects on neurophysiological outcomes. This was a novel and ambitious experimental study, which aimed to test an ecologically valid (i.e., real world) intervention which is already offered to and conducted with patients of Falls Clinics. Accessing this population required establishing and maintaining close collaborations with Physiotherapy departments in both the University (UCC) and local healthcare providers (Falls Clinic, Cork; Falls Service, University Hospital Waterford). The research project involved recruitment and experimental testing through a national hospital, in accordance with hospital procedures and ethics policies. Due to the restrictions on data collection with individuals deemed at high-risk for Covid-19 (i.e., older adults), it was not possible to complete data collection for this study. For this reason, the work in this chapter is presented as pilot data and a study protocol to inform future research. This is valuable information for researchers in this field who wish to undertake similar studies, highlighting the methodological challenges associated with accessing, recruiting and testing this population (i.e., community-dwelling older fallers). Each of these elements warrant further research in order to ensure the success of future studies with the same aim.

It is notable that the importance of the patient/participant in these kind of studies is becoming more and more relevant with participant experience being a core element of such research studies involving people's participation and the potential impact of the research for a patient population (i.e., fall-prone older adults). The final chapter (Chapter 5) documents a qualitative exploration of older fallers' experiences of participating in Study Two (Chapter Four). The global pandemic and restrictions in research activities with older individuals from February 2020 provided an opportunity to explore the personal experiences of older fallers as research participants in experimental and EEG studies, particularly in hospital settings. This, to our knowledge, is novel in the literature. Chapter Five encapsulates the Public and Patient Involvement (PPI) aspect of my PhD thesis. There is recognised value in including stakeholders and end-users of research in the research itself and older fallers represent a sub-group of the population where PPI has been overlooked, given the unique challenges associated with conducting research with fall-prone individuals. Study Three provides insights into older fallers' views on and experiences of being a research participant, highlighting how they conceptualise their falls, how they experience being a participant and their feedback on Study Two's experimental project. The findings from this qualitative work have implications for future research endeavours aiming to recruit older fallers, as insights into older fallers' motivations for participation and the aspects they considered challenging during the experiment were gained through the individual interviews. A second implication pertains to fallers' views on and interpretation of their falls, specifically their view of their falls as inevitable and possibly unpreventable, an important consideration for future intervention and prevention initiatives for falls. This work is being prepared for submission to a peer-reviewed academic journal.

Finally, Appendix A contains a peer-reviewed article published during my PhD, a piece of community research that although not directly addressing the research question of this thesis, it relates to the more broad link between physical activity and healthy ageing and the focus on physical activity promotion in this age group, which in turn, could be potentially beneficial for multisensory perception and falls prevention efforts in the future. In my journey to become an independent researcher, I felt this project had important formative value, complementing the skills acquired through the core of my PhD; research design, data collection, data analyses and research dissemination. This research project required skills more specific to the application of research for the real world. The project involved close collaboration with stakeholders (management and members of a local retirement club, older individuals living in the community) and developing a research study in conjunction with them in order to maximise the real-world value of the project for them.

Chapter Two: Can We Train Multisensory Integration in Adults?: A Systematic Review

Abstract

The ability to efficiently combine information from different senses is an important perceptual process that underpins much of our daily activities. This process, known as multisensory integration varies from individual to individual, and is affected by the ageing process, with impaired processing associated with age-related conditions, including balance difficulties, mild cognitive impairment and cognitive decline. Impaired multisensory perception has also been associated with a range of neurodevelopmental conditions, where novel intervention approaches are actively sought, for example dyslexia and autism. However it remains unclear to what extent and how multisensory perception can be modified by training. This systematic review aims to evaluate the evidence that we can train multisensory perception in neurotypical adults.

A total of 1521 studies were identified following a systematic search of the databases PubMed, Scopus, PsychInfo and Web of Science. Following screening for inclusion and exclusion criteria, 26 studies were chosen for inclusion. Study quality was assessed using the Methodological Index for Non-Randomised Studies (MINORS) tool and the Cochrane Risk of Bias tool 2.0 for Randomised Control Trials. We found considerable evidence that in-task feedback training using psychophysics protocols led to improved task performance. The question of whether such training is generalisable to other tasks of multisensory integration remains open, with existing studies showing mixed findings. Promising findings from exercise-based training indicate physical activity protocols warrant further investigation as potential training avenues for improving multisensory integration. Future research directions should include piloting training protocols with clinical populations and other groups who would benefit from targeted training to improve inefficient multisensory integration.

Keywords: multisensory, perception, perceptual training, sound-induced flash illusion, cognitive health

Outputs

At the time of completion of this thesis, this manuscript is under review with Multisensory Research.

Contributions

The lead researcher and author on this review was Jessica O'Brien, with the work supported and reviewed by Dr Annalisa Setti and Dr Jason Chan. We would like to acknowledge the support of Amy Mason (University of Limerick) with abstract and full-text article screening and Jacqueline Brennan (University College Cork) with the quality appraisal phase of the review.

Introduction

Multisensory integration refers to our brain's ability to combine information from different senses into one coherent perception of the world around us. It is a perceptual function that has seen a surge of interest in research in the past decade (Alais et al., 2010). Efficient multisensory integration underpins our perception, cognitive processing and movement control (Freiherr et al., 2013; Stein & Meredith, 1990). Multisensory deficits have been identified in a range of neurodevelopmental conditions, including schizophrenia (Williams, 2009), dyslexia (Harrar et al., 2014), Autism (Stevenson, Siemann, et al., 2014) and neurodegenerative conditions such as Parkinson's (Ren et al., 2018) and mild cognitive impairment (Murray et al., 2018; Chan et al., 2015) and it is associated with poorer global cognition (Hernández et al., 2019) and specific cognitive functions (Hirst et al., 2022; Wallace et al., 2020).

Impaired multisensory functioning has also been associated with impaired functional ability in older adults, such as unstable balance (Stapleton et al., 2014) and falling (Mahoney et al., 2019; Setti et al., 2011), highlighting the relevance of multisensory processing for successful ageing. Of note, older adults exhibit more extensive multisensory integration, with greater susceptibility to audio-visual illusions (Hirst et al., 2019; McGovern et al., 2014; Setti et al., 2011; Stapleton et al., 2014) and greater difficulty judging audio-visual synchronicity (Chan et al., 2015) compared to their younger counterparts. Older adults' extensive integration (equating to an enlarged temporal binding window (TBW; Colonius and Diederich, 2004; Diederich et al., 2008), may compensate for age-related declines in sensory acuity (Brooks et al., 2018; Hirst et al., 2019; Laurienti et al., 2006). Yet, such a compensatory strategy may yield negative consequences, given evidence that more refined integration (i.e., a narrow TBW) is associated with functional benefits

(Murray et al., 2016). Recently, Hirst and colleagues reported cross-sectional associations between multisensory integration and cognitive functioning in a large sample of older adults (*n* = 2875). The authors found an enlarged TBW (and greater susceptibility to an audio-visual illusion) was associated with poorer performance on a range of cognitive tasks requiring processing speed, attention and memory (Hirst et al., 2022). In effect, the pattern of processing whereby sensory stimuli is bound together at longer temporal spans, likely results in a less precise (or noisier) multisensory representation which may be associated with negative real world outcomes such as poorer cognitive performance and heightened falls risk.

Different cortical regions have been implicated in multisensory processing, including the frontal (specifically prefrontal cortex and premotor cortex), parietal (intra-parietal sulcus), temporal lobes (superior temporal sulcus; STS; Cappe et al., 2012; see review by Ghazanfar and Schroeder, 2006) and angular gyrus (Hirst et al., 2021). In particular, the STS has been extensively studied in terms of its association with processing multisensory stimuli (Beauchamp et al., 2004; Meredith & Stein, 1986). With growing functional evidence around the brain basis of multisensory perception, our understanding of how multisensory inputs are processed has and continues to evolve. Evidence to date suggests efficient multisensory processing relies on communication between many different brain areas and networks, both sensory-specific regions and areas of the brain traditionally associated with multisensory processing (see review by Macaluso, 2006). Given the widespread recruitment of brain regions during integration, it is possible the neural networks implicated in multisensory processing are also those affected in neurodevelopmental conditions or ageing processes associated with impaired perceptual function (Chan et al., 2021). Indeed, Mahoney and colleagues (Mahoney & Verghese, 2018) found visual-somatosensory integration abilities associated with spatial gait performance in older adults and reference the overlap in neural circuitry (cortical and sub-cortical regions) recruited for multisensory integration and locomotion. Research continues with a focus on how the process of multisensory integration occurs within the brain (e.g., neural oscillations underpinning multisensory processing (Keil & Senkowski, 2018) with some evidence for neuromodulation through training (Theves et al., 2020).

Psychophysics tasks and multisensory illusions can be used as measurement tools for quantifying a person's multisensory functioning (e.g., the Sound-induced Flash illusion (SiFI; Shams et al., 2002, see Hirst et al., 2020 for review). While audio-visual interactions dominate the literature when it comes to paradigms to study multisensory processing (Merriman et al., 2015; Stein, 2012), continued technological advances are likely to result in greater accessibility to researching multisensory interactions across different sensory modes (Cornelio et al., 2021).

With the advent of research exploring multisensory integration, and the emergence of its link to ageing and a number of neurodevelopmental and neurodegenerative conditions, the question of whether we can improve a person's multisensory processing is pertinent, given its importance in our ability to effectively interact with the world around us. The perceptual learning literature highlights the plasticity of perceptual processing, with learning observed across a range of unisensory functions, including vision, audition, touch, taste and olfaction (see Maniglia and Seitz, 2018), giving rise to training interventions for unisensory impairments (e.g., age-related visual deficits; DeLoss et al., 2015). In terms of multisensory processing, promising findings from studies of crossmodal recalibration suggest that audio-visual temporal processing is highly plastic, with evidence of perceptual realignment following passive exposure to stimuli (Noel et al., 2016; Van der Burg et al., 2013). In the last decade, a range of studies have explored the possibility of training multisensory perceptual functioning through various modes. Most studies have used computer-based psychophysics training in an effort to improve an individual's performance on tasks of multisensory perception. These have the advantage of presenting a controlled environment, where the training is administered with millisecond precision. For example, a number of training studies in the literature stem from a piece of work by Powers and colleagues in 2009, whereby a Simultaneity Judgement task was adapted for training purposes by including trial-by-trial feedback to participants (Powers et al., 2009). This study demonstrated that a person's task performance can be improved or 'trained' through in-task feedback (Powers et al., 2009). A recent critical review of multisensory integration training for older adults identified two categories of training paradigms within the literature; audio-visual temporal discrimination training and simultaneity judgement training (Pinto et al., 2022). However, other paradigms such as balance training and music have been highlighted in reviews as possible training avenues (Hirst et al., 2020; Zhou et al., 2020).

While a range of studies exist that target multisensory processing for training, the question of whether we can train multisensory perception in younger and older adults has not been systematically addressed. This review aims at collating and evaluating the evidence for the effect of training on multisensory integration in an adult population.

Material and Methods

Design

The design of this study was a systematic review of pre-post intervention studies, Randomised Controlled Trials and experimental studies aiming to train multisensory integration in an adult population. The review was conducted in line with the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) guidelines (Moher et al., 2009), comprising a systematic search of relevant databases, formulation of inclusion and exclusion criteria, a quality assessment of studies and data extraction. The review protocol was registered with PROSPERO (CRD42020185564). A systematic review of studies aiming to train multisensory perception in adults was carried out. The initial phase of the review comprised title and abstract screening (Phase 1) and was followed by a full text screening of eligible articles (Phase 2) which passed the screening from Phase 1.

Search Strategy

Two key terms (and their variations) were central to the database search; " ∗sensory integration" and "training", where "∗ " was the wild card and title/abstracts were searched for presence of these search terms. When searching multisensory integration, we used 'multisensory integration' OR 'multisensory function' OR 'multisensory interaction' OR 'multisensory binding' OR 'multisensory perception' OR 'multisensory processing' OR "temporal binding window" OR "temporal window of integration" OR 'cross-sensory integration' OR 'cross-sensory binding' OR 'cross-sensory interaction' OR 'cross-sensory processing' OR 'cross-sensory perception' OR 'cross sensory integration' OR 'cross sensory binding' OR 'cross sensory interaction' OR 'cross sensory processing' OR 'cross sensory perception'

OR ‘cross modal integration’ OR ‘cross modal binding’ OR ‘cross modal interaction’ OR ‘cross modal processing’ OR ‘cross modal perception’ OR ‘cross-modal integration’ OR ‘cross-modal binding’ OR ‘cross-modal interaction’ OR ‘cross-modal processing’ OR ‘cross-modal perception’ OR ‘bimodal integration’ OR ‘multimodal integration’ OR ‘perceptual training’. When searching training, we used ‘intervention’ OR ‘training’ OR ‘train’ OR ‘reduc*’ OR ‘improv*’ OR ‘rehab*’ OR ‘program*’. Where databases allowed, we applied filters to include age ranges of 18+ years, human participants only and English language articles only. Please see Appendix B for specific search strategies for each database searched. An initial search was carried out in 15.06.2021 and given the time lapsed between then and the subsequent write-up a renewed search was carried out on 18.08.2022.

Literature Search

PubMed, Web of Science (WOS), Scopus and PsychInfo were searched to identify eligible published studies. Studies were limited to those published in the English language or with English translated versions accessible online. See Appendix A for a full list of the search strategy used. Titles and abstracts of retrieved articles were screened and reviewed independently by two reviewers to identify suitable studies against our inclusion/exclusion criteria. For eligible studies, full text articles were retrieved for further assessment and screening. Any disagreements were resolved through a discussion centred on the articles’ fit with the research question and in relation to the inclusion/exclusion criteria. JC and AS acted as additional reviewers where JOB and AM could not reach a consensus decision on a paper. The systematic review pooled studies that aimed to train multisensory processing in an adult population. A study was included if: (1) participants comprised adults aged 18+ considered neurotypical; (2) some form of training intervention was introduced during the study (3) a quantifiable measure of multisensory perception at pre and post-training was included; (4) included Randomised Controlled Trials (RCT), non-randomized studies, case-control studies, and cohort studies. Moreover, studies were excluded if: (1) they were conference abstracts, reviews, case reports, comments, or letters; (2) data were unavailable or insufficient; (3) the populations comprised clinical groups (e.g., individuals with physical or neurocognitive conditions).

Data Extraction

Data extraction was conducted by JOB after discussing the extraction table with JC and AS. Extracted information included participant information, information on the training delivered and training outcomes for multisensory processing. This included details on study setting; study population, participant demographics and baseline characteristics; details of the training used in the study and any control conditions; study methodology; recruitment, completion and attrition rates; dependent variables and times of measurement of the outcomes; and information for assessment of the risk of bias. Specific to the training details for each study, we identified the duration of training, number of training sessions, mode of training delivery and the sensory modalities targeted during training (i.e., audio-visual, vestibular).

Risk of Bias Assessment of Included Studies

Due to the quasi-experimental and non-randomised nature of most training studies on multisensory perception, it was identified that many risk of bias assessment tools would fail to discriminate between studies in terms of quality and bias. For this reason, a grading system specifically for non-randomised experimental studies would be needed to score the majority of the studies included in our review.

A review of methodological recommendations for assessing risk of bias in non-randomised studies concluded review authors should identify the most appropriate tool for included studies, with no single tool identified as the standard (Quigley et al., 2018). Following a review of available tools, the Methodological Index for Non-Randomized Studies (MINORS) tool was selected as an appropriate tool for this purpose. Quality of methodology was assessed by JOB using the Methodological Index for Non-Randomised Studies (MINORS) assessment tool for non-randomised studies (Slim et al., 2003) and the Cochrane Risk Of Bias (ROB) tool for RCTs (Higgins et al., 2011). MINORS was chosen for its documented suitability for non-randomised or quasi-randomised experimental studies (Ma et al., 2020) and its high test-retest reliability and internal consistency (Cronbach's alpha of 0.73). For RCTs, bias was categorised as a judgement (high, low, or unclear) in the following domains of bias: selection, performance, detection, attrition, reporting and other bias. For noncomparative non-randomised studies, the MINORS scale assessed quality across twelve domains, with the first eight specific to non-comparative studies: a clearly stated aim, inclusion of consecutive patients, prospective collection of data, endpoints appropriate to the aim of the study, unbiased assessment of the study endpoint, follow-up period appropriate to the aim of the study, loss to follow-up less than 5% and prospective calculation of the study size. Items were scored as 0 (if not reported), 1 (when reported but inadequate), or 2 (when reported and adequate). The optimal total score for a MINORS assessment is 16 for non-comparative studies and 24 for comparative studies. The initial two studies were cross-scored by JOB and AS, after which JOB assessed all further studies with the exception of papers where JOB, AS or JC were authors. For papers written by authors of this review, an independent reviewer distinct from our lab group conducted these MINORS assessments.

Data Analysis

The type of training and the tasks used to assess outcomes in the studies were too heterogeneous to allow for meta analysis of the results. While a number of studies used similar testing paradigms (e.g., Sound-induced Flash Illusion task), the conditions of testing and the variations in the testing protocol varied considerably between studies. In light of this, only a qualitative synthesis of results was deemed appropriate.

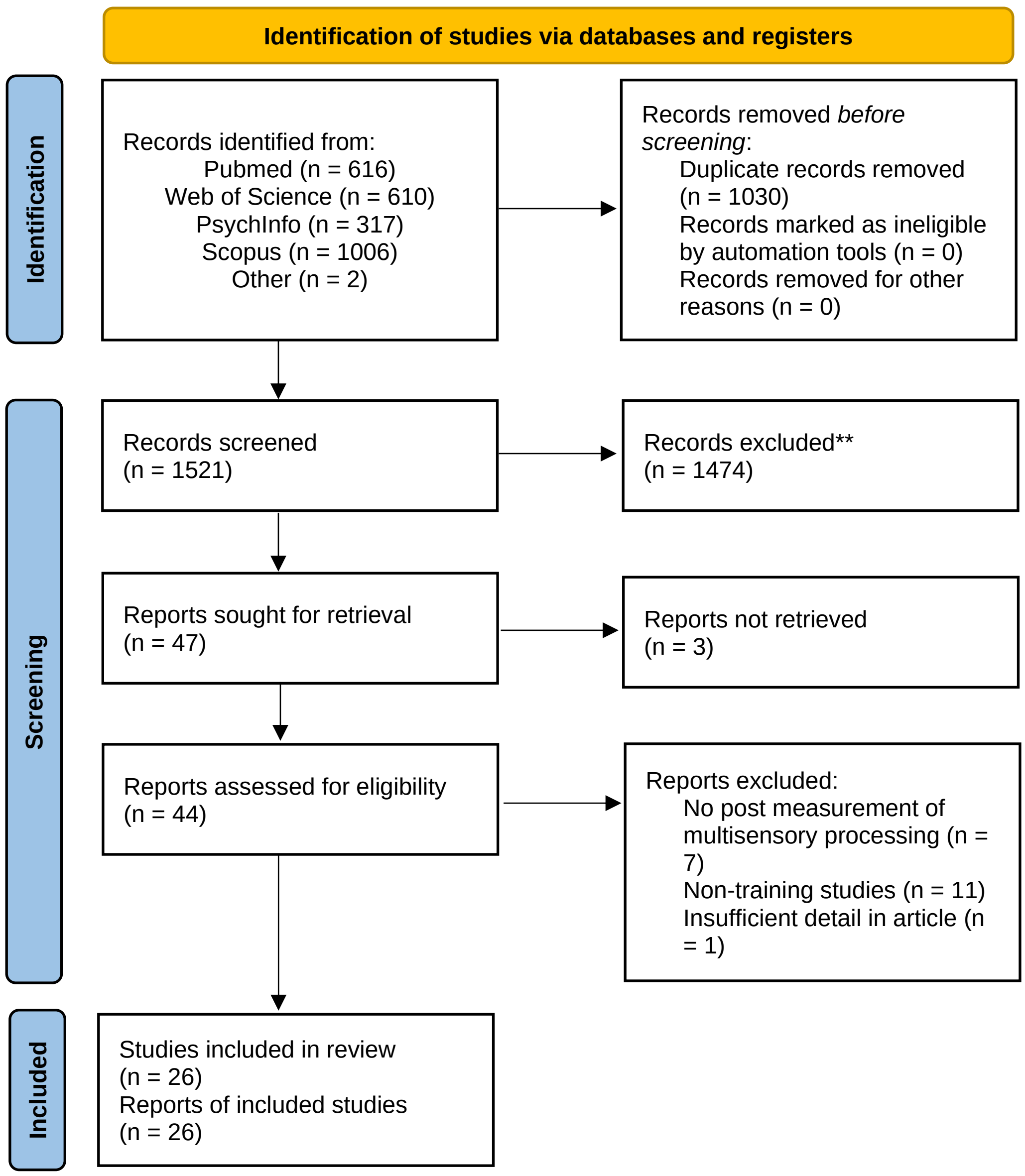
Results

Study Selection and Characteristics

The search of databases yielded 2551 hits, of which 1012 were identified by Rayyan (web application) as duplicates. A further 18 duplicate records were removed manually, leaving 1521 records for the screening phase. During the screening of title and abstracts, 1474 records were excluded as they did not meet our outlined inclusion criteria; inappropriate outcome measure (i.e., not including a pre- and post-measure of multisensory processing) accounted for 55.78% of exclusions, wrong study design (i.e., non-training studies) accounted for 25.77%, wrong population accounted for 17.37% (e.g., studies with children, clinical populations or animal studies) and wrong publication type (e.g., conference abstract) accounted for 1.08% of exclusions. Finally, 44 potentially eligible articles were further screened by reading the full-text of the articles. A number of articles (n = 11) were excluded as they did not fit criteria as a training study (e.g., two studies using Transcranial Magnetic Stimulation (TMS) as the intervention paradigm and any studies not adopting a pre post measurement approach). Following this full-text screening, 26 were deemed suitable for inclusion in the systematic review. Figure 2.1 depicts the PRISMA flow chart of the screening phases.

Figure 2.1

PRISMA Flow chart

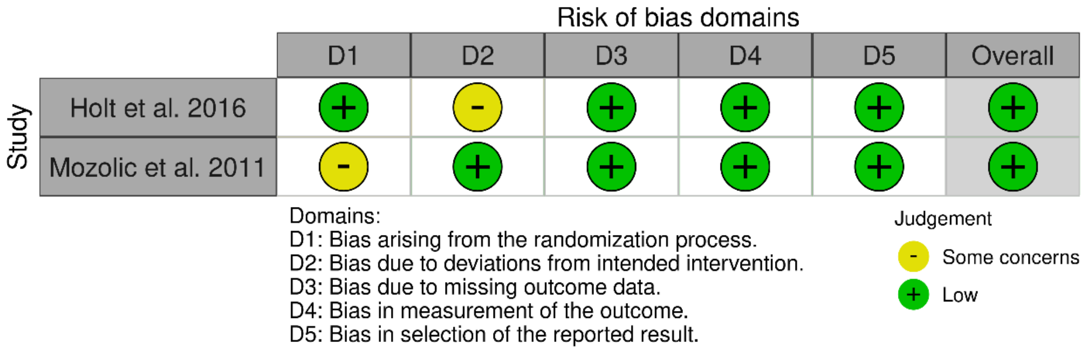


Of the included studies in this review, 2 studies were identified as RCT designs and the remaining 24 were considered non-randomised experimental studies. The RCT studies were deemed to have a low risk of bias when judged against the

ROB 2 Cochrane tool for risk of bias (see Figure 2.2 for visualisation of the individual domains).

Figure 2.2.

Visualisation of risk of bias for included studies



Of the non-randomised studies (n = 24), 21 were considered comparative studies (2 or more groups in study design) and their methodological quality was assessed against the full MINORS 12 domains. The comparative non-randomised studies averaged 17.94 (range: 16-20) out of a possible score of 24 for methodological quality. Four of the non-randomised studies were deemed non-comparative studies and scored against the first 8 of the MINORS domains, in line with scoring guidelines for this tool. The four non-comparative studies scored 11, 11, 12 and 13 points respectively (out of a possible 16 points) for methodological quality.

Overall, all included non-randomised studies scored 0 (not reported) on one item; 1. unbiased assessment of study endpoint (blind evaluation of endpoints or reasons for non-blinding indicated). With the exception of one study (Kramer et al., 2020), all studies scored 0 (not reported) on the item related to power calculation; 2. prospective calculation of study size (power estimates provided). See Table 2.1 for a breakdown of each study's score on MINORS items.

Table 2.1
Scores on MINORS scale

	Clearly stated aim	Consecutive participants	Prospective data collection	End points appropriate to aims	unbiased assessment of study endpoint	follow-up period appropriate to aims	loss of follow-up less than 5%	prospective calculation of study size	adequate control group	contemp orary groups	baseline equivalenc e of groups	adequate statistical analyses	Total Score
Powers et al. 2009	2	2	2	2	0	2	2	0	2	2	0	2	18
O'Brien et al., 2017	2	2	2	2	0	2	1	0	2	2	1	2	18
Setti et al., 2014	2	2	2	2	0	2	2	0	1	2	2	2	19
Theves et al., 2020	2	2	2	2	0	2	1	0	n/a	n/a	n/a	n/a	11/16
DeNiear et al., 2016	2	2	2	2	0	2	2	0	0	2	1	2	17
Rosenthal et al., 2009	2	2	2	2	0	2	1	0	n/a	n/a	n/a	n/a	11/16
Merriman et al., 2015	2	2	2	2	0	2	1	0	2	2	2	2	19
Stevenson et al., 2013	2	2	2	2	0	2	2	0	2	2	1	2	19
Appiah-Kubi & Wright, 2013	2	2	2	2	0	2	2	0	2	2	1	2	19
Yang et al., 2018	2	2	2	2	0	2	2	0	2	2	2	2	20
Powers et al., 2016	2	2	2	2	0	2	2	0	2	2	1	2	19
DeNiear et al., 2018	2	2	2	2	0	2	2	0	2	2	1	2	19
Zerr et al., 2019	2	2	2	2	0	2	2	0	1	2	2	2	19
Alais & Cass 2010	2	2	2	2	0	2	2	0	0 (no control)	2	0	2	16
Surig, Bottari & Roder, 2018	2	2	2	2	0	2	2	0	2	2	1	2	19

McGovern et al., 2016	2	2	2	2	0	2	2	0	0 (no control)	2	0	2	16
Pantev et al., 2015	2	2	0 (pre-existing data)	2	0	2	2	0	2	2	0	2	16
O'Brien et al., 2020	2	2	2	2	0	2	1	0	0 (young control)	2	N/A	2	15
De Niear, Noel & Wallace, 2017	2	2	2	2	0	2	2	0	2	2	0	2	18
Virsu et al., 2008	2	2	2	2	0	2	2	0	n/a	n/a	n/a	n/a	12/16
Cecere, Gross & Thut, 2016	2	2	2	2	0	2	1	0	1	2	1	2	17
Kramer, Roder & Bruns, 2020	2	2	2	2	0	2	1	2	n/a	n/a	n/a	n/a	13/16
Mc Govern et al., 2022	2	2	2	2	0	2	1	0	n/a	2	2	2	17
Huang et al., 2022	2	2	2	2	2	2	2	2	1	2	1	2	22
Horsfall, Wuerger & Meyer, 2021	2	2	2	2	2	2	1	0	1	2	0	2	18

Synthesised Findings

Eligible studies were assessed in terms of the study sample, study design, training paradigm used and the study's findings in relation to the effect of training on multisensory integration. Table 2.2 at the end of the results section outlines a summary of findings from the included studies as well as results in relation to the transfer of training to untrained tasks. Refer to Appendix B for a tabular detailed overview of the twenty-six studies included in the review.

Study sample

The vast majority of studies included in this review drew participants from the young adult age group (Appiah-Kubi and Wright, 2019; Cecere et al., 2016; De Niear et al., 2018, 2017, 2016; Kramer et al., 2020; McGovern et al., 2016; Pantev et al., 2015; Powers et al., 2009; Powers et al., 2016; Stevenson et al., 2013; Virsu et al., 2008; Zerr et al., 2019), with some of these studies (n = 5) specifically recruiting undergraduate students and university staff. One study had a sample of healthy adults, including both young and middle-aged adults (Rosenthal et al., 2009). Seven studies included samples of community-dwelling older adults (Holt et al., 2016; McGovern et al., 2022; Merriman et al., 2015; Mozolic et al., 2011; J. O'Brien et al., 2017; J. M. O'Brien et al., 2020; Setti et al., 2014; Yang et al., 2018), with three of these studies including groups of both older and younger adults to compare the effects of training between age groups (McGovern et al., 2022; J. M. O'Brien et al., 2020; Yang et al., 2018). Of the seven studies including an older age cohort, three studies referenced fall-prone older adults amongst their sample (Merriman et al., 2015; J. M. O'Brien et al., 2020; Setti et al., 2014), with one of these studies aiming to address the emerging link between falls risk and multisensory integration directly

(Merriman et al., 2015). Reporting of participant characteristics represents a weak point of the included studies, with thirteen of the included twenty-six studies failing to provide comprehensive details on age characteristics of their samples, including age ranges, mean ages and standard deviations. It is also noted that one study included the study authors within the participant sample (Alais & Cass, 2010), while a common practice for experimental studies of this nature, it represents a weakness in the study design and quality, due to the potential risk of biases with such a study design. This reflects a justified concern, considering the increasing relevance in this literature of top-down processing, such as voluntary attention and decision-making (see Jones and Noppeney, 2021).

Training Paradigm

Most studies (*n* = 19) included in this review used computer-based psychophysics-type training, which involved training perception using stimuli presented on a computer screen or other technology. Many of the studies based their training on Powers and colleagues work (Powers et al., 2009), where an audio-visual Simultaneity Judgement task was adapted to include trial-by-trial feedback in order to train participants' performance on the task. In Powers and colleagues (2009) original experimental work, both 2-Interval-Forced-Choice (2-IFC) and 2-Alternative-Forced-Choice (2-AFC) paradigms were trialled. In 2-IFC training, participants are presented with two separate pairs of stimuli (a pair of auditory and visual stimuli) followed by a second pairing, one of which pairing comprises the stimuli being presented synchronously and another pair where there is a time lag between presentation of the stimuli. Participants are required to decide which of the pair of stimuli was presented synchronously by pressing a key corresponding to pair one or pair two. In the 2-AFC version of training, participants are presented with a pair of stimuli (auditory and visual stimulus) and tasked with judging whether the stimuli occurred synchronously or asynchronously. Powers and colleagues reported significantly reduced TBW size after a single session of either 2-AFC or 2-IFC training. Interestingly, for both training groups, further improvements were not observed across the remaining four training days. One week follow-up revealed both groups' TBW size was significantly smaller at follow-up compared to baseline. In 2016, Powers and colleagues investigated if their training procedure would generalise to other multisensory tasks (Powers et al., 2016). Participants were tested on the SiFI task before and after 5 days of either 2-AFC or 2-IFC training. Powers et al (2016) reported no generalisation of training to SiFI performance as participants only displayed improvements in visual temporal acuity on the task (i.e., detecting 2 visual flashes) but did not change in their susceptibility to the illusion. Of note is that in these studies the SOAs are fixed and not tailored to the initial or on-task performance of the individual.

Three studies utilised versions of the 2-AFC training paradigm featured in the original Powers et al. (2009) study (Cecere et al., 2016; Sürig et al., 2018; Zerr et al., 2019). Sürig and colleagues (2018) trained participants for 5 sessions on the 2-AFC task with staircase procedure and a control group who completed the 2-AFC training with random SOAs (i.e., no control over difficulty increments). Sürig et al. (2018) reported faster perceptual learning in the experimental group, with significantly reduced perceptual thresholds after a single day of training. Those in the control group displayed significant reductions in thresholds after 4-5 training sessions. Training effects for the experimental group transferred to performance on a spatial localisation task and a redundant target task; the control group did not exhibit any transfer of training to performance on the other tasks (Sürig et al., 2018). Zerr and colleagues (2019) also found positive effects of 2-AFC training following 3 days of training, with participants displaying significantly narrower TBWs compared to the control group who completed unisensory training. The authors found training benefits persisted at a 7 day follow-up but observed no significant effect of training length on performance and found training did not transfer to performance on the SiFI task (Zerr et al., 2019). Cecere and colleagues (2016) adapted the 2-AFC task by training 3 groups of participants on auditory-leading stimulus pairs, visual-leading stimulus pairs and a final group who trained on both. Two-day training led to the group who were trained on both variations displaying improved perceptual sensitivity (d prime) on visual-leading trials only. No variation of training led to significant improvements on the auditory-leading pairs (Cecere et al., 2016). Using a staircase procedure on a 2-AFC task, Virsu and colleagues (2008) demonstrated that explicit feedback was not necessary for improved simultaneity judgements. By recruiting university students to practice the task for 8 sessions across 2 months, they found improved mean SOA thresholds and significant practice gains on performance of audio-visual, audio-tactile and visual-tactile synchronicity judgements (Virsu et al., 2008). To note that this was a lengthy training compared with the previous. Finally, another study trained participants for a single session on the 2-AFC paradigm, manipulating the intensity of the visual stimulus (bright vs dim stimuli training group), reporting that only those trained on the bright stimuli showed reduced TBW which did not generalise to performance on dim stimuli (Horsfall et al., 2021).

Three studies employed the 2-IFC paradigm documented in Powers et al. (2009) original training paper (De Niear et al., 2016, 2018; J. M. O’Brien et al., 2020). De Niear and colleagues (2016) trained 3 groups of young adults for 1 day of

2-IFC training, with groups comprising easy, medium or difficult levels of the 2-IFC task, i.e., difficult group given training with SOAs at which correctly determining synchronicity is rare (based on individual's baseline performance across a range of SOAs). The authors found only participants in the difficult group displayed significantly reduced TBW post-training, whereas those in the easy training group had enlarged TBW post-training. A later study by De Niear and colleagues (2018) explored two different formats of 2-IFC training, one with flash/beep stimuli (i.e., standard visual and auditory stimuli) and another using speech-based stimuli (i.e., video of speaker as visual and speech sounds as auditory stimuli). Specificity of training was observed such that each group only displayed improved temporal acuity on the task they were trained on; the flash-beep group did not improve on the speech 2-IFC and vice versa. Of note, only those who received the flash-beep training showed sustained reduced TBW at one week follow-up. Another study conducted with young adults using a 3 day 2-IFC staircase paradigm found improved audio-visual discrimination post-training as well as a significantly reduced TBW measured using ventriloquist task (authors report near 50% reduction; McGovern et al., 2016). Selective transfer of training effects to spatial integration was reported, with no effect of training on the spatial binding window but a reduction in the magnitude of the ventriloquist effect across all measured spatiotemporal disparities post-training (McGovern et al., 2016). In a study aiming to investigate if older adults can be trained on the 2-IFC paradigm, community-dwelling older adults completed 3 days of training (O'Brien et al., 2020). The authors reported both younger and older adults improved in their ability to discriminate simultaneity correctly in the 2-IFC task, with significantly reduced TBW post-training. Training did not generalise to performance on the SiFI task for either age cohort (O'Brien et al., 2020). Contrasting results were reported by a recent study, also utilising 2-IFC training with young and older adults, whereby training effects generalised to reduced susceptibility to the SiFI and reduced TBW based on the SiFI fission illusion (1-flash/2-beep trials) for both groups (McGovern et al., 2022). While both age groups showed reduced susceptibility to the SiFI fusion illusion (2-flashes/1-beep trials), only younger adults showed reduced TBW post-training.

A further three studies adopted a Temporal Order Judgement task (TOJ) with feedback as the training paradigm (Alais & Cass, 2010; Setti et al., 2014; Stevenson et al., 2013). Alais & Cass (2010) trained participants for 8 days using a TOJ with staircase procedure with young adults and found participants trained on the audio-visual TOJ showed improved discrimination thresholds. Participants who received single modality TOJ training (i.e., visual or auditory) did not show improved discrimination thresholds on the audio-visual TOJ task. By contrast, Stevenson and colleagues (2013) found visual TOJ training led to improved audio-visual integration, evidenced by reduced TBW during a 2-IFC audio-visual simultaneity judgement task. Setti and colleagues (2014) trained older adults for 5 days on an audio-visual TOJ task with in-task feedback. For individuals who trained (i.e., demonstrated improved task performance post-training), training effects transferred to reduced susceptibility to the Sound-induced flash illusion.

An additional study trained young and older adults on an audio-visual discrimination task and utilised EEG to measure Event Related Potentials (ERP) during an audio-visual discrimination task completed post-training (Yang et al., 2018). Training comprised 4 days per week for a duration of 4 weeks with in-task feedback on synchronicity judgements between pairs of audio-visual stimuli. Control groups of young and older adults underwent EEG testing but did not complete any training between testing sessions. Audio-visual task accuracy (i.e., correctly identifying if stimuli spatiotemporally consistent or not) improved post-training for both the younger and older adults who received training, no change in task accuracy was found for either of the control groups. For the older adults, improved performance was accompanied with significantly greater P300 amplitudes post-training.

Two studies used the SiFI task with feedback as the training paradigm (Huang et al., 2022; Rosenthal et al., 2009). Rosenthal and colleagues (2009) authors reported no effect of a single session of feedback training on SiFI performance except when a monetary reward was offered for accuracy of performance (i.e., correctly identifying number of flashes in conditions of the SiFI). However, a recent study found 7 days of feedback training resulted in reduced SiFI susceptibility and narrowing of the TBW based on the fission illusion (Huang et al., 2022). A novel paradigm was utilised by Kramer, Roder and Bruns (2020) to explore the effect of feedback training on the ventriloquism effect (i.e., visual influence during auditory localisation, a proxy measure of multisensory integration). Using six loudspeakers to deliver auditory stimuli across different spatial locations and laser dots as the visual stimulus, participants were tasked with localising the auditory stimulus during audio-visual trials. Kramer et al. (2020) found reduced ventriloquism effect (equating to more efficient multisensory integration) when participants were provided with feedback about the location of the auditory stimulus.

Mozolic and colleagues' (2011) RCT trained older adults' attention on a multisensory task for 8 sessions across 8 weeks, finding significant reductions in integration during multisensory trials involving selective visual and auditory attention but not in trials requiring divided attention. Pantev and colleagues (2015) used music reading as the training paradigm with young adult participants, incorporating melodies and a visual of pitch height as the respective auditory and visual stimuli used when participants tasked with judging congruency or incongruency of stimuli. Five sessions of music reading training were associated with changed MEG activity in the auditory cortex, such that the task conditions requiring audio-visual integration resulted in neurofunctional changes in the left auditory cortex which is associated with audio-visual processing. By comparison, the control conditions involving processing of visual and auditory separately resulted in neurofunctional changes in the parts of the auditory cortex related to auditory processing, with no effect on areas linked to audio-visual processing.

Several studies adopted a form of physical exercise or movement as the training paradigm, mainly referencing the link between multisensory integration and balance control. The types of activity used in the training studies varied but included usual physical activity (J. O'Brien et al., 2017), 2017), exergames (Merriman et al., 2015), and specific protocols like chiropractic care (Holt et al., 2016) and vestibular training (Appiah-Kubi & Wright, 2019). A study in 2017 (J. O'Brien et al., 2017) recruited community-dwelling older adults and tested their performance on the SiFI task before and after a session of their regular physical activity. Participants were divided into two groups based on the type of their usual physical activity (open-skill exercise: aerobics class, tennis, dance class; closed-skill exercise: gym circuits, swimming). The study found only participants who engaged in a bout of open-skill exercise showed improved perceptual sensitivity on the SiFI task.

One study (Merriman et al., 2015) explored the effects of balance training using exergames on multisensory integration efficiency in older adults. The Wii balance board and virtual environments were used to train older adults' balance over

5 weeks of 2 training sessions per week. Merriman and colleagues (2015) reported no change in SiFI susceptibility following training. However, the authors noted a trend for fall-prone older adults to display improved SiFI accuracy (i.e., decreased SiFI susceptibility) following training as well as a correlation between improved balance scores and reduced susceptibility to the SiFI for fall-prone participants who underwent the intervention. A study by Appiah-Kubi and Wright (2019) used a force plate to train young adult participants with postural training (i.e., weight-shifting exercises) guided by a physical therapist. The training involved two short sessions (15 mins) per day, every second day for a week, totalling 6 training sessions. A control group received no training. Experimental participants were divided into a Headshake and No Headshake group, which manipulated vestibular activation during postural training (i.e., headshake equates to vestibular activation). The Headshake group showed improvements in the somatosensory (SOM) ratio of the Sensory Organisation Test, which indicates a significant somatosensory up-weighting for this training group. The control and No Headshake groups did not display any significant changes in somatosensory functioning.

A RCT conducted by Holt and colleagues (2016) explored the potential multisensory benefits of regular chiropractic care (12 weeks) for older adults. A control group did not receive chiropractic input but attended all other usual healthcare appointments. Older adults who received chiropractic care showed reduced susceptibility to the SiFI illusion at 4 week and 12 week assessments. At the 12 week assessment, the authors report the chiropractic group improved on SiFI performance by 13.5% compared to the control participants.

Outcomes from training

In terms of outcome variables, many studies used performance on the training task as the outcome measurement, e.g., if participants trained on the Temporal Order Judgement (TOJ) task, the dependent variable was post-training performance on the TOJ. Some studies used task accuracy (i.e., proportion/percentage correct responses to task conditions) or mean scores to explore training effects, with many finding feedback training improves task performance on a range of audio-visual tasks (Cecere et al., 2016; Huang et al., 2022; McGovern et al., 2022; O'Brien et al., 2020; Powers et al., 2009; Setti et al., 2014; Sürig et al., 2018; Yang et al., 2018). One study did not adopt feedback training but found improved task performance on an audio-visual task following attention training (Mozolic et al., 2011). Other dependent variables included perceptual sensitivity scores (d prime) or the temporal binding window (TBW), both of which were estimated based on task performance. Improved d prime was reported in one study (Cecere et al., 2016) and approached significance in another (Setti et al., 2014), while reduced TBW was reported in 8 feedback training studies (De Niear et al., 2016, 2017, 2018; Horsfall et al., 2021; O'Brien et al., 2020; Powers et al., 2009; Stevenson et al., 2013; Theves et al., 2020; Zerr et al., 2019). Perceptual thresholds were used in few studies, with reduced absolute value for point of subjective simultaneity reported in one study (PSS; De Niear et al., 2017), improved TOJ onset discrimination (Alais & Cass, 2010) and improved mean SOA thresholds in another study (Virsu et al., 2008).

Transfer of training

Many studies explored generalisation of training effects by employing perceptual illusions, most often, the Sound-induced flash illusion (SiFI) to gain a proxy of a participants' multisensory integration. Participants were asked to perform the SiFI task which included consistent or inconsistent audio-visual stimuli.

Multisensory integration was operationalised as susceptibility to the illusion, whereby experiencing fewer illusions is equated to more efficient multisensory integration in line with young adults performance (see Shams et al., 2002). Training was found to benefit SiFI performance in some studies, either through improved d prime scores or reduced susceptibility to the illusion (i.e., mean percent correct on illusion trials improving post-training (Holt et al., 2016; Huang et al., 2022; McGovern et al., 2022; O'Brien et al., 2017; Setti et al., 2014). By contrast, four of the included studies in this review found no improvement for SiFI performance following training (Merriman et al., 2015; O'Brien et al., 2020; Powers et al., 2016; Zerr et al., 2019) and one study reported improved performance on the SiFI task only when a monetary reward was offered for correct performance (Rosenthal et al., 2009)). Two studies used an alternative perceptual illusion paradigm to estimate multisensory integration efficiency, the ventriloquism effect (VE), whereby visual stimuli modulates processing of auditory stimuli (Kramer et al., 2020; McGovern et al., 2016). Both studies found reduced susceptibility to the ventriloquism effect post-training.

Worth noting is a pattern that emerges in the psychophysics studies using the SiFI measure as an outcome of training transfer. Training studies that utilise increasing task difficulty (e.g., staircase procedures) see transfer of training to reduced SiFI susceptibility or improved sensitivity on the SiFI task (McGovern et al., 2022; Setti et al., 2014), whereas training studies that randomly present trials (i.e., no systematic increase in difficulty based on participant performance) do not see transfer of training benefits to the SiFI task (O'Brien et al., 2020; Powers et al., 2016; Zerr et al., 2019). The work of both Sürig et al. (2018) and Mc Govern et al.

(2016), who also use training with systematic increases in difficulty also find training transfers to improved performance on other multisensory tasks.

Transfer of audio-visual training to spatial integration was reported in two studies (McGovern et al., 2016; Sürig et al., 2018), using 2-IFC and 2-AFC Simultaneity Judgement training respectively. Less congruent results were reported for the effects of unisensory training (i.e., visual training) on multisensory integration. While Stevenson and colleagues (Stevenson et al., 2013) found 5 day visual TOJ training led to improved TBW based on the 2-IFC paradigm, Alais and Cass (2010) did not find improved discrimination thresholds for unimodal or multimodal trials following 8 days of unimodal training.

Several studies point to the specificity of training effects to trained stimuli. Training using bright stimuli did not transfer to performance using dim visual stimuli (Horsfall et al., 2021), with another study finding training benefits specific to the attentional demands of the task, with improved performance during selective but not divided attention conditions (Mozolic et al., 2011). De Niear and colleagues (De Niear et al., 2018) found training using traditional visual and auditory (flash beep) stimuli did not transfer to the same task using audio-visual speech stimuli and vice versa. However, this contrasts with results from Zerr and colleagues (Zerr et al., 2019) who found training-induced narrowing of the TBW was associated with improved speech perception.

Three studies utilised neurophysiological outcome measurements to operationalise multisensory processing (Pantev et al., 2015; Theves et al., 2020; Yang et al., 2018). Two studies using MEG data found that following training, participants showed significantly changed patterns of activation during multisensory task completion, specifically elevated beta band activity in cortical and parietal regions (Theves et al., 2020) and changed activity in the left auditory cortex (Pantev et al., 2015). In their study exploring changes to the P300 component following training, Yang and colleagues (2018) reported greater P300 amplitude post-training for older but not younger adults. A single study used the somatosensory ratio (generated by the Sensory Organisation Test), demonstrating improved somatosensory processing (i.e., upweighting) following vestibular training (Appiah-Kubi & Wright, 2019).

Table 2.2
Summary of included studies

Psychophysics training	Training Type	Modalities trained	No. of training sessions/duration (session duration)	Effect of Training (effect size)	Transfer of Training (effect size)
younger adults					
Powers et al. (2009)	2-IFC vs 2-AFC SJ with feedback	audio-visual	5 sessions/5 days (60 mins)	Significant improvement in task performance and reduced TBW. Significant effects were seen after a single day of training and persisted at 1 week follow-up	n/a
Powers et al. (2016)	2-IFC vs 2-AFC SJ with feedback	audio-visual	5 sessions/5 days (60 mins)	n/a	No generalisation to SiFI susceptibility. Only visual temporal acuity improved (2 flashes). Improved *d'* found and significant correlations between decrease in TBW and increased *d'* (*R squared* = 0.2)
Cecere et al. (2016)	2-AFC SJ with feedback	auditory- and visual-leading pairs (group 1), auditory-leading pairs (group 2), visual leading pairs (group 3)	2 sessions/2 days (n.d.)	Improved sensitivity to visual-leading stimulus pairs for groups who received visual-leading pairs (*Cohen's d* = 1.69) and combined auditory-leading and visual-leading training (*Cohen's d* = 1.11).	Training group who received both auditory-leading and visual-leading stimulus pairs showed increased sensitivity (*d'*) on visual-leading trials. No training group showed improvements on auditory-leading pairs.
Surig, Bottari & Roder (2018)	2-AFC SJ with feedback	audio-visual	5 sessions/10 days (n.d.)	Faster learning in experimental group (staircase procedure) compared to control (random presentation). Discrimination thresholds decreased following first training session and remained constant	Transfer to spatial ventriloquist effect and redundant target task

Zerr et al. (2019)	2-AFC SJ with feedback vs. SJ unisensory training	audio-visual	3 sessions/3 days (4-5 mins)	Improved task performance (*partial eta squared = 0.29*). AV training narrows TBW significantly more than unisensory training. Benefits persisted at 7 day follow-up	No transfer to SiFI susceptibility. Narrowing of TBW associated with better speech perception (WRT)
Virsu et al. (2008)	2-AFC SJ with feedback	Auditory, visual, tactile, audio-visual, audio-tactile, visual-tactile	8 sessions/8 weeks (approx between 18-40 mins)	Improved performance on unimodal and multimodal tasks from pre-training to 7 month follow-up. Training gains significantly diminished over 7 month follow-up vs. immediately post-training.	
McGovern et al. (2016)	2-IFC SJ with feedback	audio-visual, spatial	3 sessions/3 days (n.d.)	Training led to improved audio-visual discrimination for both groups (temporal and spatial groups) (n.d.)	Significant reduction (near 50%) in TBW (measured by ventriloquist task). Selective transfer to spatial binding window (reduction in amplitude for visual stimuli positioned on right of midline but not left)
De Niear et al. (2016)	2-IFC SJ with feedback (easy vs. moderate vs. hard difficulty based on SOA groups)	audio-visual	1 session/1 day (n.d.)	Hard group improved on task performance and showed reduced TBW at post-training. Easy group resulted in significantly enlarged TBW at post-training.	n/a
De Niear et al. (2017)	SJ task with feedback	audio-visual	1 session/1 day (90 mins)	Significant narrowing of TBW for all groups. Narrowing of TBW occurred more rapidly for feedback groups (n.d.)	n/a
De Niear et al. (2018)	2-IFC SJ with feedback (flash-beep vs. speech stimuli vs. exposure)	audio-visual	4 sessions/4 days (n.d.)	Both training groups improved on temporal acuity of trained task. Flash-beep task improvement in TBW (narrower) was sustained at 1 week follow-up. Exposure (control) group saw no narrowing of TBW (n.d.)	No transfer of training to untrained tasks (e.g., flash beep group did not improve on AV speech task and vice versa)

Theves et al. (2020)	2-IFC SJ with feedback	audio-visual	1 session/1 day (30-35 mins)	Improved task performance following training (*U squared* = 0.99). Reduced TBW (*Cohen's d* = 1.6).	Improved temporal acuity accompanied by elevated beta band activity post training (measured using MEG)
Alais & Cass (2010)	AV TOJ with feedback	audio-visual	8 sessions/8-13 days (n.d.)	Improved AV discrimination thresholds for AV TOJ training (*R squared* = 0.87). Participants in Single-modality TOJ training did not show improved thresholds.	n/a
Stevenson et al. (2013)	Visual TOJ with feedback	Visual	5 sessions/5 days (n.d.)	Improved visual TOJ performance post-training (*partial eta squared* = 0.02)	Reduced TBW on 2-IFC SJ task post-training (*partial eta squared* = 0.04). Correlation found between initial TBW width and training gains, with wider TBW associated with greater training-induced narrowing (*R squared* = 0.73)
Rosenthal et al. (2009)	SiFI with feedback	audio-visual	1 session/1 day (60 mins)	SiFI was found to be resistant to feedback training. However, reduced SiFI susceptibility was found when monetary reward offered for correct performance and feedback provided.	n/a
Pantev et al. (2015)	AV music reading training	audio-visual	5 sessions/1 week (28 mins)	n/a	Training group showed neuroplastic effect (changed MEG activity) in auditory cortex (associated with AV processing)
Kramer, Roder & Bruns (2020)	AV task with feedback	audio-visual, spatial	4 sessions/varied (n.d.)	Magnitude of ventiloquism effect modulated by feedback. When feedback about position of auditory stimulus provided, reduced ventriloquism effect observed	n/a
older adults					
Mozolic et al. (2011)	Attention training during multisensory task	audio-visual	8 sessions/8 weeks (60 mins)	Improved ability to ignore irrelevant crossmodal stimuli	Reductions in integration during modality-specific selective attention (auditory or visual) conditions, but not during divided attention conditions

Setti et al. (2014)	AV TOJ task with feedback	audio-visual	5 sessions/5 days (30 mins)	75% (18 of 24) participants successfully trained on AV TOJ task	Reduced SiFI susceptibility for participants who successfully trained vs. untrained and control group *(partial eta squared* = 0.27). SiFI susceptibility post-training correlated with size of TBW post-training (n.d.)
young vs. older adults					
Yang et al. (2018)	AV discrimination task with feedback	audio-visual	16 sessions/4 weeks (n.d.)	Improved task performance for both age groups (n.d.)	Improved task performance accompanied by greater P300 amplitude post-training for older adult group (n.d.)
O'Brien et al. (2020)	2-IFC SJ with feedback	audio-visual	3 sessions/3 days (n.d.)	Improved temporal acuity on 2-IFC task (*partial eta squared* = 0.23) and reduced TBW post-training (*partial eta squared* = 0.21)	No generalisation to SiFI performance for either age group (*d* = 0.4)
Mc Govern et al. (2022)	2-IFC SJ wth feedback	audio-visual	3 sessions/3 days (n.d.)	Improved task performance for both age groups evidenced by reduced discrimination thresholds (*Cohen's d* = 1.12 (young and 1.07 (older)	Reduced susceptibility to the SiFI fission illusion (*partial eta squared* = 0.53 (young) and 0.44 (older) as well as a significant narrowing of TBW based on fission illusion, *Cohen's d* = 0.74 (young) and 1.03 (older). Reduced susceptibility to fusion illusion (*partial eta squared* = 0.39 (young) and 0.33 (older), with only young group showing reduced TBW based on fusion illusion (*Cohen's d* = 0.64)
Huang et al. (2021)	SIFI with feedback	audio-visual	7 sessions/7 days (n.d.)	Reduced susceptibility to fusion and fission illusion. Compared to control, training group displayed reduced susceptibility to fission illusion, *Cohen's d* = 1.12 but not on fusion illusion at post-test. Linear trend for improvement with pattern of stabilisation after day 5	n/a
Horsfall et al. (2021)	2-AFC SJ task with feedback (auditory beeps); bright stimuli groups vs. dim stimuli group	audio-visual	1 session/1 day (n.d.)	Training using bright stimuli led to reduced TBW using bright stimuli (*partial eta squared* = 0.43). Group trained with dim stimuli did not see reduction in TBW post-training	Training on bright stimuli did not transfer to performance on dim stimuli, with no effect on TBW

Exercise/ movement training					
young adults					
Appiah-Kubi & Wright (2019)	Postural training	n/a	6 sessions/1 week (15 mins)	Improved postural stability	Vestibular activation group (Headshake Group) showed improved somatosensory performance on SOT
older adults					
Merriman et al. (2015)	Balance exergame	n/a	10 sessions/5 weeks (30 mins)	Improved balance and postural control	No transfer to SiFI performance but correlation between improved balance scores and reduced SiFI susceptibility for fall-prone participants only
Holt et al., (2016)	Chiropractic care	n/a	12 weeks (varied)	Improved sensorimotor function	Reduced susceptibility to SiFI across week 4 and week 12 assessments
O'Brien et al. (2017)	Acute exercise bout	n/a	1 session/1 day (approx 30 mins)	n/a	Open-skill exercise group: improved perceptual sensitivity on SiFI

Discussion

To our knowledge, this is the first systematic review of the evidence which explores whether multisensory integration can be improved through training protocols. Since Powers and colleagues (2009) initial training study which aimed to improve audio-visual synchronicity judgements through computer-based psychophysics experiments, several research studies have emerged to explore the possibility of training multisensory processing. This review sheds light on the nature of these studies, their quality and their combined findings. A search of the existing literature identified 26 studies for inclusion in this review. A quantitative analysis of the studies was not deemed appropriate given the variability in outcome measures and protocols across studies. A qualitative synthesis of the evidence was therefore conducted. This is an interesting finding in itself, as it shows that a harmonization of paradigms and specific task characteristics could be beneficial for the field going forward.

Of the 26 included studies, the majority adopted psychophysics-based training protocols, using computer-based tasks to deliver sensory stimuli and evaluating participants’ performance on tasks requiring the integration of stimuli from different senses. The types of protocols used in studies included variations of Powers and colleagues’ (2009) original experiment, the 2-Interval-Forced-Choice task, requiring a judgement on whether stimuli were synchronous or not or the 2-Alternate-Forced-Choice task, requiring a response on whether the stimuli were presented synchronously or asynchronously. Other computer-based perceptual paradigms included the Temporal Order Judgment task and novel audio-visual tasks. In general, the data from these studies find that performance on perceptual tasks of this nature can be improved with training, with improved task performance, reduced

TBWs and improved perceptual thresholds reported in many studies. Feedback training, whereby participants receive in-task feedback on their performance (i.e., correct or incorrect on each trial) successfully improved participants task performance in 16 studies (Alais & Cass, 2010; Cecere et al., 2016; De Niear et al., 2016, 2017, 2018; Horsfall et al., 2021; McGovern et al., 2022; Mozolic et al., 2011; J. M. O'Brien et al., 2020; Powers et al., 2009; Setti et al., 2014; Stevenson et al., 2013; Sürig et al., 2018; Theves et al., 2020; Yang et al., 2018; Zerr et al., 2019). Interestingly Virsu and colleagues found explicit feedback was not needed to improve task performance (Virsu et al., 2008), however this training protocol was much longer than the others utilising feedback. Together, these studies provided considerable evidence as to the trainability of perceptual task performance, specifically computer-based bi-modal integration (most often audio-visual integration).

Many of the included studies utilised the concept of the temporal binding window (TBW) to explore training effects on multisensory integration. The TBW refers to a timeframe during which temporally close stimuli are likely to be integrated into a single unified percept (Colonius & Diederich, 2004). The shape of the TBW changes over the course of development, with a gradual narrowing of the window throughout adolescence (see Hillock-Dunn and Wallace, 2012) and a widening of the window observed in older adults (see review by Zhou et al., 2020). Generally, it is accepted that a narrow window reflects efficient multisensory integration and a number of training studies report reduced TBW size following perceptual training (e.g., Powers et al., 2009). This effect could be explained in the context of the Bayesian inference model, where 'practice' or learning leads to a reduced casual prior and hence more correct audio-visual temporal judgments. Jones and Noppeney (2021) recently highlighted a number of factors that can contribute to the Bayesian effect (in the context of age-effects on multisensory processing), including decision-making strategies, perceptual priors, attention and the reliability of unisensory information. Further research is needed to explore the mechanisms of training effects on multisensory processing, considering the range of factors associated with audio-visual integration and TBW shape (see Zhou et al., 2020). Reviewing the included studies highlights a complex picture in relation to the specificity of training effects, with conflicting findings regarding transfer to untrained tasks. The included studies point to transfer of audio-visual training to spatial integration (McGovern et al., 2016; Sürig et al., 2018), yet there is mixed evidence when it comes to specificity to trained stimuli and trained modality. For example, DeNiear et al.'s study (2018) using speech-based audio-visual stimuli vs. the original stimuli used in Powers et al.'s (2009) work, found improved temporal acuity only on the task trained, i.e., perceptual training using speech based stimuli did not transfer to performance on the same task using non-speech based stimuli. Training did not transfer when the following deviated from the training protocol; visual stimulus intensity (Horsfall et al., 2021), and attentional demands (Mozolic et al., 2011); conflicting evidence was found for transfer beyond stimulus modality (see Alais and Cass, 2010; Stevenson et al., 2013). Other studies found the difficulty of trials affected training gains, such that only individuals trained with more challenging SOAs improved post-training (De Niear et al., 2016; Sürig et al., 2018), raising the question of optimal training features to induce improved performance. Despite mixed evidence of training transfer on behavioural tasks, it is encouraging to see emerging evidence that training multisensory processing induces neuroplastic effects in the brain (Pantev et al., 2015; Theves et al., 2020; Yang et al., 2018).

Specificity of training was also reflected in the conflicting evidence regarding the generalisability of perceptual training to other tasks, as many studies included perceptual illusions as additional outcome measures. Perceptual illusions serve as a proxy measure of multisensory integration, and the SiFI was the illusion paradigm most used in the literature. While two studies reported transfer of perceptual training to reduced susceptibility to the SiFI (McGovern et al., 2022; Setti et al., 2014)), many more studies reported that psychophysics-type training on audio-visual synchronicity judgements did not generalise to improved performance on perceptual illusions (O'Brien et al., 2020; Powers et al., 2016; Zerr et al., 2019). Of note, the studies which showed training transfer involved training paradigms with increasing trial difficulty (e.g., staircase procedure; (McGovern et al., 2022; Setti et al., 2014), whereas the other studies which did not systematically vary task difficulty did not result in transfer to the SiFI task. This points to the potential role of task difficulty in generalisation of training, an avenue meriting further research. Interestingly, studies that used open-skill exercise (J. O'Brien et al., 2017) and chiropractic care (Holt et al., 2016) found improved performance on the SiFI, yet exergame training did not affect SiFI performance (Merriman et al., 2015). This speaks to the potential value of training of multisensory processing utilising daily activities, which prompt integration of real world multisensory inputs as opposed to computer-based stimuli. Further studies are needed in this context, especially noting that O'Brien et al. (2017) utilises one bout of physical exercise, while Holt et al.'s (2016) training consists of several sessions of chiropractic intervention, potentially speaking to different underlying mechanisms.

Consideration must be given to the issue of training generalisability, given that cognitive training programmes enjoy limited success when applied beyond controlled research settings (Sala & Gobet, 2019), with very few programmes found to have benefits for real world or clinical outcomes (see Rebok et al., 2014; and see meta-analysis by Sala et al., 2019). Additionally, the perceptual learning literature has also highlighted the specificity of perceptual training effects for unisensory processing, with benefits often specific to the exact task trained and raising the issue of unrealised real world impact (Green et al., 2018; Shams & Seitz, 2008). In their review of the perceptual learning literature, Green and colleagues (2018) noted that training paradigms that were associated with more general benefits involved real-world experiences (e.g., video games, music training) as opposed to lab-based experiments. In light of this, there is value in exploring training approaches that are more naturalistic and potentially user-friendly such as physical exercise for potential benefits for multisensory functioning. Physical activity has known benefits for cognitive functioning (see reviews by Gomez-Pinilla and Hillman, 2013; Ratey and Loehr, 2011), and it is plausible perceptual functions should also see benefit. Indeed, physical exercise has been associated with efficient unisensory integration (Prioli et al., 2005) and visual-somatosensory integration (Mahoney et al., 2015) in older adults, with exercise thought to combat age-related changes in visual, somatosensory and vestibular systems (Shumway-Cook & Woollacott, 2007). Physical activity may represent a natural activity which trains multisensory functioning, as recruitment of multisensory processes is required to move within and navigate our environments (Bronstein, 2016). The findings of the present review provide additional weight to the argument that the research into the exercise-cognition link should extend to focus on perceptual processing, given the promising results seen in the few available studies.

Considering the limited evidence available to date, it is premature to draw conclusions around whether computer-based versus real-world training approaches are more effective for training multisensory processing, yet further research is warranted to elucidate the mechanisms of training this perceptual function.

Of note is that the study sample of the majority of the studies were young adult groups (n = 19), with the remaining studies (n = 7) recruiting older adults. The focus on older adults is intuitive given the growing literature linking functional ability and falls-risk to multisensory processing in later life (see Zhang et al., 2020 for review). Considering the predominance of young adult sample groups, specifically university student samples (in 5 studies), this speaks to the exploratory nature of research in this area, considering these groups as convenience samples in terms of accessibility and availability for research participation. Now that there is considerable evidence for the trainability of multisensory integration in neurotypical young adults, there is now need to expand research to investigate whether multisensory integration can also be trained in population groups most likely to benefit from such an intervention, i.e., cohorts who display deficits in multisensory integration.

Limitations

This study has a number of limitations. Firstly, the articles included in this review were relatively homogenous in experimental paradigms, with many adopting psychophysics designs for training (TOJ, SJ), and using sensory illusions (e.g., SiFI) as a proxy measure for multisensory integration, despite the task-specific differences. For those studies that explored other training modes (e.g., exercise or movement-based approaches), the lack of empirical studies precludes any definitive conclusion as to their effectiveness for improving multisensory processing. Also, the possibility of reporting bias cannot be discounted in terms of selective reporting of positive results from training. For experimental studies, most included studies have small sample sizes and most showed no evidence of apriori power calculation or double-blinding. With only two RCTs available for inclusion in this review, the quality of the evidence must be taken into consideration when reviewing the evidence base, in particular the limited information available to rule out comorbidities and confounding factors. Finally, we also note the variability between studies in terms of training dose (i.e., number of training sessions) and training session duration, with many articles not including detailed information around time spent in training and specifics of time lapsed between training sessions. While the depth of information in the included studies is lacking, it is evident that more studies (particularly those employing an RCT design) are needed to establish the evidence for training protocols to improve multisensory efficiency, in populations who display impaired multisensory processing (e.g., patients with MCI (Chan et al., 2015)).

Conclusion

Multisensory integration is an ever-growing field in the literature, and as research into its' origins and role in various conditions (physical or neurological) grows, investigations into how we can improve inefficient multisensory integration should also see further research. This review highlights the malleability of this perceptual process, with many existing studies successfully training multisensory integration in groups of young and older neurotypical adults. Taking together the evidence presented here, it is clear that multisensory integration warrants the focus of our research efforts, presenting as a promising candidate for intervention; emerging as a perceptual process displaying plasticity with training as well as being impaired in specific cohorts (i.e., neurodegenerative and neurodevelopmental conditions) for which we require novel and effective intervention avenues.

Chapter Three: Study One – Audio-visual Training in Older Adults: 2-Interval-Forced Choice Task Improves Performance

Abstract

A growing interest in ameliorating multisensory perception deficits in older adults arises from recent evidence showing that impaired multisensory processing, particularly in the temporal domain, may be associated with cognitive and functional impairments. Perceptual training has proved successful in improving multisensory temporal processing in young adults, but few studies have investigated this training approach in older adults. In the present study we used a simultaneity (or synchronicity) judgement task with feedback, to train the audio-visual abilities of community-dwelling, cognitively healthy older adults. We recruited 23 older adults (*M* = 74.17, *SD* = 6.23) and a group of 20 young adults (*M* = 24.20, *SD* = 4.23) who served as a comparison. Participants were tested before and after perceptual training using a 2-Interval Forced Choice Task (2-IFC); and the Sound-induced Flash Illusion (SiFI). After 3 days of training, participants improved on the 2-IFC task, with a significant narrowing of the temporal window of integration (TWI) found for both groups. Generalization of training effects was not found, with no post-training differences in perceptual sensitivity to the SiFI for either group. These findings provide evidence perceptual narrowing can be achieved in older as well as younger adults after 3 days of perceptual training. These results provide useful information for future studies attempting to improve audio-visual temporal discrimination abilities in older people.

Outputs

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Contributions

The first author on this work is Jessica O'Brien, who completed data collection, data analyses and write-up. Dr Annalisa Setti and Dr Jason Chan designed the study, supervised and reviewed data analyses and write-up.

Introduction

The appropriate integration of inputs coming from the different senses is a crucial ability to support an efficient interaction with the environment (Alais et al., 2010; Freiherr et al., 2013; Murray et al., 2016; de Dieuleveult et al., 2017). One of the ways in which the brain determines the appropriateness of this integration is based on the temporal features of the incoming stimuli; if the inputs from different senses fall within the temporal window of integration (TWI), they are combined into a unitary percept; otherwise they are processed as separate events (Vroomen and Keetels, 2010). In turn, the size of the TWI is associated with our sensitivity in discriminating the order of temporally asynchronous stimuli (Stevenson et al., 2012), which can be determined with tasks such as temporal order judgments (TOJ) or synchronicity judgments (Chan et al., 2014b; Setti et al., 2014; Bedard and Barnett-Cowan, 2016; Scurry et al., 2019; Theves et al., 2020).

Older adults show larger temporal order thresholds (i.e., the minimum temporal interval leading to correct discrimination) than younger adults (Bedard and Barnett-Cowan, 2016), enhanced susceptibility to audio-visual illusions (Setti et al., 2011; McGovern et al., 2014), increased difficulty judging audiovisual synchrony (Chan et al., 2014a), and reduced audio-visual recalibration compared to young adults (Chan et al., 2014b). They display an enlarged TWI (Colonius and Diederich, 2004; Diederich et al., 2008), and enhanced benefits in perceiving congruent multisensory stimuli, with cognitive (Laurienti et al., 2006), and functional benefits (Mahoney and Verghese, 2018). However, an enlarged TWI may be disadvantageous when inputs from different senses are incongruent, as shown utilizing the Sound-induced Flash Illusion (SiFI; Setti et al., 2011; Chan et al., 2015). A wider TWI in older adults could be related to their decreased unisensory abilities, as, in line with the principle of Inverse Effectiveness, greater gain is obtained by combining weaker unisensory stimuli (Holmes, 2007). According to the TWI model (Colonius and Diederich, 2011) integration occurs very rapidly. The start of peripheral processing of sensory inputs (regardless of modality) triggers the opening of the TWI; when the SOA between the unisensory stimuli is sufficiently short to allow for completion of the processing of both stimuli within the window, then the inputs are integrated. Multisensory integration is thought to occur based on the likelihood reliability of inputs from the different modalities for the task at hand (Maximum Likelihood Estimation and Information Reliability (Schwartz et al., 1998). Therefore, reduced unisensory ability would change the likelihood of integration and enhance reliance on prior knowledge, or perceptual priors (Ernst and Banks, 2002; Chan et al., 2017), which is associated with a wider TWI in older adults.

Considering the potential benefits of efficient multisensory integration (Murray et al., 2016), refining the TWI by enhancing the temporal discrimination abilities of individuals presents a potential avenue for supporting or improving cognitive and functional abilities in older adults with cognitive and functional deficits (Setti et al., 2011; Chan et al., 2015; Mahoney and Verghese, 2018; Murray et al., 2018; Hernández et al., 2019).

In healthy young adults, cross-sensory temporal discrimination abilities have been successfully improved through perceptual training (Powers et al., 2009, 2016) by exposing participants to pairs of stimuli separated by different temporal intervals and asking them to determine either: which one came first, the visual or the auditory, or whether they were synchronous and providing informative feedback. Specifically, such training paradigms included asking participants to determine the temporal order of stimuli (Temporal Order Judgment, TOJ), just asking whether stimuli were synchronous (2-AFC), or judging which pair of stimuli of two sets were presented simultaneously (2-interval forced choice, 2-IFC; see Stevenson and Wallace, 2013). Powers et al. (2009) utilized two training tasks, a two-alternative forced choice task (2-AFC) and a two-interval forced choice (2-IFC) task. In the first paradigm, participants are asked to decide whether two stimuli (one visual and one auditory) appeared simultaneously or not (2-AFC). In the second paradigm, participants are exposed to two sets of audio-visual stimuli, and they are asked to decide in which pair, the first or the second, the stimuli were simultaneous (2-IFC). The 2-IFC paradigm has also been used in two variants: with one pair always portraying physical simultaneity (Stevenson and Wallace, 2013) or where both pairs are not simultaneous and the task was to indicate which pair was closer to simultaneity (Yarrow et al., 2016). In Powers et al. (2009) the first type of 2-IFC was utilized. During training, feedback was provided on whether the participant answered correctly. Young participants were trained for 5 days, and with both paradigms they had a marked narrowing of the TWI. In a follow up study (Powers et al., 2012), participants showed a significant narrowing of the TWI after only 1 day of 2-IFC training. This behavioral improvement was coupled by decreases in BOLD activity post-training in the posterior Superior Temporal Sulcus (pSTS) and in primary visual and auditory areas of the cortex (Powers et al., 2012). This decrease in BOLD activity can be associated with an increase in beta-band activity, as they have been shown to have a negative relationship (Conner et al., 2011; Hanslmayr et al., 2011). Furthermore, using dynamic causal modeling, Powers et al. (2012) found effective connectivity between sensory areas and pSTS changed from a mainly feedforward model (pre-training) to a more evenly distributed effective connectivity between brain areas, post-training. It has been suggested in some neural models (e.g., predictive coding) that increased beta-band activity represents increased template information (Mumford, 1992; Arnal and Giraud, 2012; Bastos et al., 2012; Bastos, 2013), which would be in line with these results (Powers et al., 2012). More recently, Theves et al. (2020) used magnetoencephalography (MEG) to investigate the neural oscillations associated with a reduced TWI. Using the same paradigm as Powers et al. (2012), they found increased beta-band activity (12–25 *Hz*) post-training compared to pre-training. Therefore, the increase in beta-band activity after training can be due to improved perceptual models associated with the TWI (Theves et al., 2020).

In relation to older adults, the work of Theves et al. (2020) is promising, as increased perception in the SiFI was associated with an overall increase in beta-band activity in younger adults (Theves et al., 2020). One would expect that perceptual training could potentially modify effective connectivity in older adults as well (with a related modulation of beta-band activity) although to test this hypothesis is beyond the scope of the present study. Older adults have also shown to be susceptible to audio-visual training. Using a different paradigm (i.e., an audio-visual temporal order judgment utilizing a staircase procedure), Setti et al. (2014) found narrowing of the TWI in healthy older participants was possible, although not all individuals actually showed the beneficial effects of training. In the same study, older participants who did show a narrowing of the TWI also showed decreased susceptibility to the SiFI, indicating potential benefits to appropriately discriminate or integrate multisensory stimuli in a different task. However, with the 2-IFC task by Powers et al. (2016), a sample of young adults had only limited benefits in terms of susceptibility to the SIFI, i.e., benefits were related to when there was the same number of beeps and flashes, not when they were incongruent.

Considering older adults' exhibit inefficient multisensory processing in the form of an enlarged TWI (Laurienti et al., 2006) and emerging evidence that this perceptual function is critical for balance control and functional mobility (Mahoney et al., 2019; Zhang et al., 2020), , identifying methods to promote efficient multisensory processing in older adults is paramount. In the present study, we investigate whether perceptual training which has proved beneficial for younger adults' multisensory processing capabilities (i.e., Simultaneity Judgment training) is effective for older adults. We adopted the 2-IFC paradigm with a sample of community-dwelling older adults to test, behaviorally, whether a reduction of the TWI can be obtained in older adults and if it can be associated with a reduction in susceptibility to the SiFI. While there is some evidence that lifestyle factors, such as physical exercise, may modulate SiFI perception in older adults (O'Brien et al., 2017); lab-based perceptual training, at present, appears to be a partially successful way to narrow the TWI and modulate susceptibility to the SIFI (Setti et al., 2014), which, in turn, is associated with cognitive performance and mobility. The literature on multisensory perceptual training in older adults is still limited, deserving further investigation.

We hypothesized that if the 2-IFC can be used successfully with older adults we should find training benefits after 3 days of targeted perceptual training. If training is successful, we expect improved performance on the 2-IFC task and reduced TWI in participants' who train. In order to assess for the generalizability of the training, we also tested participants on the SiFI, in line with Setti et al. (2014), and hypothesized that following successful training, participants should be less susceptible to the illusion. In addition, to ensure that the training protocol could replicate the successful results of Powers et al. (2009) with younger adults, we tested a group of young adults with the same methodology utilized for older adults, expecting young adults to improve in their performance on the 2-IFC task following training. We also hypothesize that training should generalize to improved sensitivity on the SiFI task in line with studies by Setti et al. (2014) and Powers et al. (2016) finding benefits for SiFI performance following perceptual training.

Materials and Methods

Participants

Two groups of participants were recruited: an older adult group and young adult group. Twenty-three older adults (10 female) aged between 60 and 85 (*M* = 74.17, *SD* = 6.23) participated. These participants were living independently in the community at the time of the study. The young adult group comprised 20 adults aged between 18 and 35 (*M* = 24.20, *SD* = 4.23). All participants reported normal or corrected-to-normal vision and hearing. Older participants were recruited through local active retired groups, community groups and community Falls groups. An analysis of the older group found no significant difference between those considered fallers (n = 11) and non-fallers (n = 12) on mean scores on any of the SiFI unisensory control conditions or dependent variables i.e., performance on 2-IFC task or SiFI task; $p > 0.8$). Young adult participants were recruited through university mailing lists and snowball recruiting. Data collection for the older adult group yielded a total of 28 participants, 5 were excluded from analyses procedures; 4 did not complete the full 3 day experimental protocol and 1 participant was identified as an outlier on control conditions of the SiFI (indicating poor sensory acuity or misunderstanding of the task instructions). See Table 3.1 for descriptive characteristics for each group.

Table 3.1

Descriptive characteristics per training group

	Older	Younger	p value
N	23	20	
Age	74.17 (6.23)	24.20 (4.23)	-
Gender	M: 13 (56.52%), F: 10 (43.48%)	M: 9 (45%), F: 11 (55%)	0.45

Note. Mean values with standard deviations in parentheses

No participants reported any psychiatric or neurological conditions that would preclude them from the study. The older adults (n = 23) and young adults (n = 20) did not significantly differ in their gender identification (Pearson chi square = 0.57, p = 0.45).

We conducted research on a separate cohort of participants (n = 20) investigating whether training that focused on the asynchrony of stimuli, instead of their simultaneity would be more beneficial (i.e., more similar to a TOJ's task demands, as TOJ was utilized by Setti et al., 2014). Due to the global Covid-19 pandemic, data collection for a young group on this alternative training protocol was not possible, please see Appendix C for data on this older asynchronous group.

Ethical approval was granted by the Ethics Committee at the School of Applied Psychology, University College Cork. All guidelines set out by the Declaration of Helsinki were adhered to.

Demographic Data

Data on participants' age, gender and regular physical activity levels (IPAQ; Booth, 2000) were collected via self-report questionnaires. Additional questionnaires for the older adult group collected information on falls-risk and global cognitive health (SMMSE). The questionnaire on falls-risk asked participants to rate their steadiness while seated, standing, in motion etc. This study is part of a wider study on falling, the data on falls are not utilized for the purpose of this study.

Baseline Measures

Sound-induced Flash Illusion (SiFI). The Sound-induced Flash Illusion (SiFI; Shams et al., 2002) was used to assess participants' multisensory integration efficiency. The SiFI consists of the illusory perception of two flashes (a white dot subtending 2◦ of visual angle, presented for 16 ms at 8◦ of visual angle below the fixation cross on a black screen background) when one flash is presented simultaneously with two beep sounds (3,500 *Hz*, duration 16 ms, 20 *µs* rise and-decay, 68 *dBA* sound pressure level). The SiFI task was administered using a Dell desktop computer (24-inch screen). The software suite Presentation (version 18; Neurobehavioral Systems) was used to program and administer the SiFI. Volume and brightness were kept constant for all participants. All participants reported no difficultly in seeing or hearing the stimuli. Participants were seated for the task, approximately 50 cm from the computer screen. Closed-back, circumaural headphones (AKG K271) delivered the auditory stimuli. For the task, participants were asked to report the number of flashes seen on the computer screen. Responses were made using the keyboard numbers (0, 1, 2, etc.). Control unisensory trials (single flash or double flash trials and single beep or double beep trials) were also presented. The trials of interest were the illusory trials, where one flash was presented with two beeps. The stimulus onset asynchrony (SOA) between the stimuli (i.e., between first the flash/beep pair and second beep) varied according to the trial. The SOAs were 70, 110, 150, and 230 ms. The visual-only and multisensory trials were presented 6 times per SOA condition (total of 84 trials). The auditory only trials were presented in a separate block, twice per condition, 1 beep and 2 beeps (at each SOA) for a total of 10 trials. The measurement of interest was the mean proportion of correct responses to illusory trials. Participants fixated on a white central fixation cross (1 × 1 cm) presented on a black background. The fixation cross remained constant throughout the task, disappearing only for the presentation of trials.

Pre and post training 2-IFC task. Participants' ability to discriminate perceptual synchrony was assessed using a 2-IFC task as in Powers et al. (2009). The same computer and apparatus were used to administer this task as described for the SIFI task. During the task, participants were asked to judge which pair of stimuli are synchronous or occurred simultaneously. For each trial in this task, participants were presented with two pairs of stimuli; each pair had a white annulus and an auditory beep. In each trial, one pair was always presented synchronously while the other was asynchronous. There was a 1,000 ms gap in between each interval. The asynchronous pairs varied by SOA (50, 100, 150, 200, 250, 300 ms). The choice of SOAs for the training reflects those utilized in successful training with younger adults, and it is in line with Setti et al. (2014). In their study, also conducted with older adults, the audio-visual temporal order judgment (TOJ) staircase converged at an SOA of approximately 250 ms before training. After 5 days of audio visual TOJ training, the staircase converged at an SOA of approximately 150 ms (depending on the group), therefore it was plausible to hypothesize that older adults would be able to perform the task, at least at the longer SOAs (200, 250, 300 ms). Participants were instructed to select the interval pair in which the stimuli were presented synchronously (i.e., simultaneously). Participants responded verbally (first or second pair) and the experimenter recorded the response using the computer keyboard (pressing either the "1" or "2" button). A response was required for each trial. Participants were instructed to give their best guess if they were unsure of the answer. Participants did not receive feedback after each response.

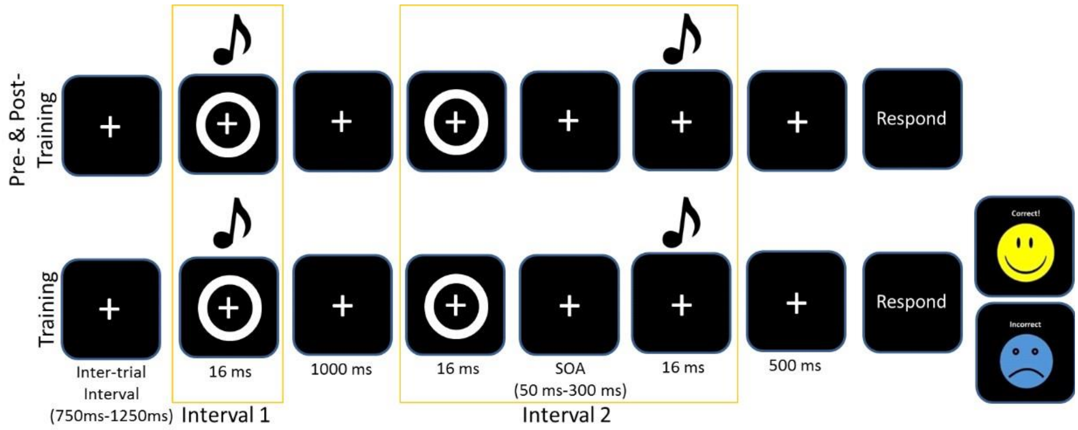
For the visual stimulus, a white annulus surrounding the fixation cross (8.8 degrees of visual angle at 50 cm distance) was utilized and presented for 16 ms against a black background. The auditory beep was a 1,800 *Hz* tone with duration 16 ms (Powers et al., 2012). The stimulus was presented to both ears via circumaural headphones (AKG K271; audibility was subjectively checked with participants). Visual and auditory stimuli were presented at SOAs ranging from 50 to 300 ms at 50 ms intervals, with visual-lead only. Each condition was repeated 24 times. The set of stimuli was kept constant for all participants (see Powers et al., 2009) for additional methodological details of this task.

Perceptual Training Protocol

The training protocol consisted of completing the same 2-IFC task but with informative feedback after each trial. After each response, feedback was given on screen with the word "correct" and a yellow smiley face appearing on screen or if the participant selected the wrong pair, the word "incorrect" would appear on screen with a blue sad face (see Figure 3.1).

Figure 3.1

Example of one trial of the 2-IFC task for the assessment pre/post and the training. Asynchronous trials always presented the visual stimulus first. The training protocol included feedback



Again, participants were instructed to select the stimulus pair which was synchronous (i.e., the pair in which the circle and beep occurred simultaneously). All participants had a 5 min break during the training to combat fatigue. As with the perceptual task and the SiFI task, participants responded verbally, and the experimenter entered responses into the computer. We chose to train participants for 3 days, as the 2-IFC had been a successful paradigm with younger adults for both 5 days and 1 day, and pilot work for Setti et al. (2014) suggested that 3 days was the minimum to register positive change in older adults. Figure 3.1 illustrates the training and test protocols. For further details on the Training task, see (Powers et al., 2009).

Procedure

Participants completed three successive testing sessions, Days 1, 2, and 3. On Day 1, participants completed the demographics questionnaires and the two pre-training measures (SiFI and 2- IFC Task) followed by the first session of training.

On Day 2, participants completed the second session of training. On Day 3, participants completed the third session of training followed by the two post-training measures. Participants were tested individually in a quiet room. For all tasks, participants were seated in front of the computer screen with the experimenter sitting beside them. Participants who normally wore glasses or contact lenses wore them for the experiment.

The order of the pre-training test was consistent across participants. Participants always completed the SiFI first, followed by the 2-IFC task and the training protocol. At post-training, participants completed the final training session, followed by the 2-IFC post-training task and the SiFI, in that order.

Analysis

Analysis of Variance was utilized to compare the groups when assumptions were met. Greenhouse-Geisser corrections were applied where Mauchly's test of sphericity was breached. Nonparametric statistical analyses were utilized to account for the skewed distribution of the TWI and of the SiFI illusory data. For each non-parametric ANOVA, care was taken to define the appropriate permutations for a factorial design (see Anderson and Braak, 2003 for methods; Suckling and Bullmore, 2004). To avoid confounds due to the within-participant factor when estimating main effects, observations for both levels of within participant factors were kept together for each participant. Only whole participants were allowed to be exchanged during the permutation procedure. No exact permutation tests, based on the *F*-statistic, exist for the interaction effect, since restricting permutation of the observations such that neither group nor condition main effect affects the corresponding *F*-ratio, would leave no possible permutations of the data. An approximate test can be constructed by restricting permutations of condition levels to occur within participant and subsequently permuting whole participants across groups (Anderson and Braak, 2003; Suckling and Bullmore, 2004; Theves et al., 2020).

In the SiFI task, the dependent variable was *d'* scores, which reflects perceptual sensitivity and performance on the SiFI task (Chan et al., 2014b; McGovern et al., 2014; Setti et al., 2014). *d'* captures a participant's ability to correctly perceive 2 flashes when they are real (i.e., correctly detecting 2 flashes in 2flash/2beeps conditions) relative to their susceptibility to the illusion (i.e., incorrectly perceiving 2 flashes in 1flash/2beeps conditions). Sensitivity was calculated using the following formula: *d'* [*z*(hits) – *z*(false alarms)]; where hits were the proportion of correct responses on 2flash/2beeps conditions and false alarms were the proportion of incorrect responses to 1flash/2beeps conditions. *z* refers to the inverse cumulative norm (Green and Swets, 1966).

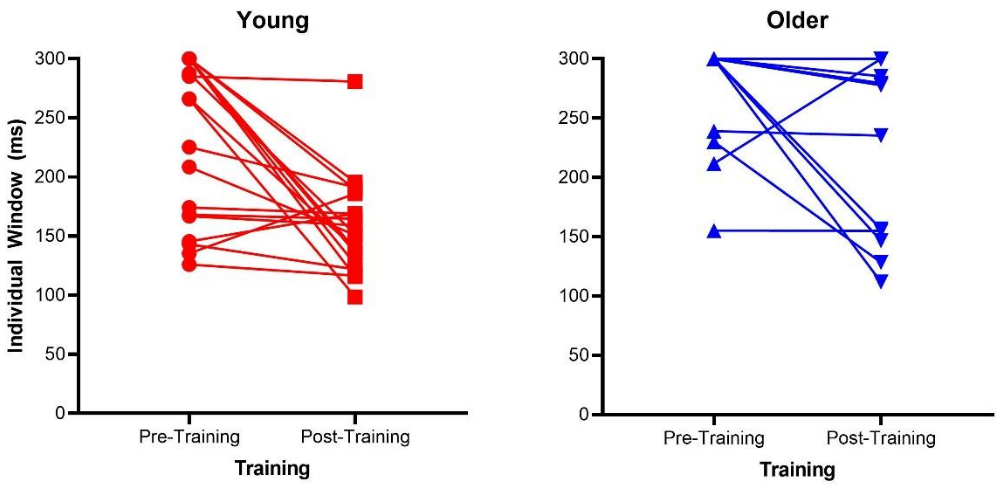
Results

2-IFC Task

A three-way mixed ANOVA was performed on the mean proportion of correct scores per SOA (e.g., mean value of 0.2 represents 20% correct scores on the task). Group (younger, older) was the between-participants factor and Time (pretraining vs. post-training) and SOA were the within-participants factors. There was a significant main effect of Group [$F(1, 41) = 41.21$, $p < 0.001$, $\eta_p^2 = 0.5$], Time [$F(1, 41) = 12.31$, $p < 0.001$, $\eta_p^2 = 0.23$] and SOA [$F(3.25, 133.14) = 64.01$, $p < 0.001$, $\eta_p^2 = 0.61$]. The main effect of Group was driven by the young group having higher mean scores (proportion of correct answers) than the older group. The main effect of Time was due to both groups having higher mean proportion correct at post-training compared to pre-training (younger: pre-training *M* = 0.73, *SD* = 0.09; post-training *M* = 0.78, *SD* = 0.68; older: pre-training *M* = 0.56, *SD* = 0.09; post-training *M* = 0.62, *SD* = 0.12). The main effect of SOA was expected, with higher mean proportion correct at longer SOAs and lower mean scores at shorter SOAs. The interaction between SOA and Group was significant [$F(3.25, 133.14) = 12.59$, $p < 0.001$, $\eta_p^2 = 0.24$] with the young group having significantly higher mean scores for each SOA compared to the older group ($p < 0.05$). There was no interaction between Group and Time [$F(1, 41) = 0.14$, $p = 0.72$, $\eta_p^2 = 0.003$]. There were no other significant interactions. Mean proportion of correct responses for each SOA is a very crude measure of the TWI, therefore we calculated the size of the individual windows, a 3rd order polynomial probability curve was fitted across the SOAs for each participant. The size of each participant's TWI was defined as the SOA at an accuracy level (i.e., correct response) halfway between the individuals' lowest accuracy point and 100% (as in Theves et al., 2020). Appendix C provides supplementary material on the calculation of the TWI for one participant. See Figure 3.2 for a scatterplot of each individual TWI. In order to analyse the TWI, a non-parametric 2 × 2 mixed ANOVA using 10% trimmed means was conducted. Group (older vs. younger) and Time (pre- vs. post-training) were the respective between participants and within-participants factors.

Figure 3.2

Scatterplots of individual Temporal Window of Integration (TWI) pre- and post-training for the older adult and young adult groups. The dotted lines represent the fitted lines for individual data



There was a main effect of Group [$F(1, 26.42) = 34.32$, $p < 0.001$, $\eta_p^2 = 0.46$] and a main effect of Time [$F(1, 26.46) = 10.95$, $p = 0.003$, $\eta_p^2 = 0.21$]. Additionally, there was a significant interaction between these two factors [$F(1, 26.46) = 4.72$, $p = 0.038$, $\eta_p^2 = 0.1$]. To follow up the significant interaction effect, non-parametric Wilcoxon Signed-Rank tests were conducted on each group separately with Time as the within-participants factor (pre-, post-training). This test confirmed the older groups' TWI significantly reduced ($Z = 6$, $p = 0.03$) from pre- ($M = 284.165$, $SD = 37.92$) to post-test ($M = 259.84$, $SD = 66.8$), as did the young group ($Z = 24.85$, $p = 0.001$), with a significantly reduced TWI at post-training ($M = 165.05$, $SD = 51.01$) compared to pre-training ($M = 232.86$, $SD = 67.93$). The daily training is presented in Appendix C.

Sound-induced Flash Illusion: Pre- and Post-training

The proportion of correct responses to the SiFI task are reported in Table 3.2 Prior to assessing participants' susceptibility to the SiFI, it was first necessary to determine their ability to perceive the auditory and visual stimuli used during the task. To this end, we analyzed participants' ability to perceive unisensory conditions (1 flash, 2 flashes, 1 beep, 2-beeps trials) and non-illusory multisensory conditions (2 flash and 2 beeps trials) at baseline (pre-training) using Mann-Whitney U-tests. There were no group differences in perceiving one flash (U = 240, p = 0.35), one beep (U = 240, p = 0.35), nor one-flash/one-beep, whereby all participants scored 100% correctly. There were no significant differences between the two groups on the multisensory control conditions (2 flashes/2 beeps) at each SOA.

There was a group difference in both unisensory control conditions (2-flashes and 2-beeps conditions). Groups significantly differed on performance on 2-flashes (U = 361.5, p = 0.001), with the older group registering significantly fewer correct responses (average of 78%) than their younger counterparts (over 90% correct). Of note, both groups had significantly fewer correct at SOA 70 ms compared to longer SOAs (mean proportion correct, older = 53%; younger = 76%). For the 2-beeps condition, there was a significant difference in mean scores (U = 294.5, p = 0.047), however this difference should be interpreted with caution as 9 participants were excluded due to missing data for SOA 110 ms due to a technical error. Group differences were due to the older group registering fewer correct scores on the 2-beeps condition (average proportion correct of 92.75% at pretraining and 88.5% at post-training) compared to the younger group (over 98% at pre- and post-training). The group differences in discriminating unisensory conditions was noted and is acknowledged in the discussion. See Appendix C for group means on each unisensory condition. A three-way Mixed ANOVA was performed on the mean d' scores for the illusion condition, with Time (pre-training, post-training) and SOA (70, 110, 150, 230 ms) as the within participants factors and Group (older, younger) as the between participants factor. There was no significant main effect of Time [$F(1, 41) = 0.83$, $p = 0.37$, $\eta_p^2 = 0.02$]. There was a significant main effect of Group [$F(1, 41) = 37.35$, $p < 0.001$, $\eta_p^2 = 0.48$] with simple contrasts revealing young adults performed better (i.e., had higher perceptual sensitivity scores) than the older group [contrast estimate = 0.66, $p = 0.02$]. There was a significant main effect of SOA [$F(3, 123) = 24.75$, $p < 0.001$, $\eta_p^2 = 0.38$]. Simple contrasts revealed participants performed significantly better at the longest SOA (230 ms) compared to shorter SOAs 70 and 150 ms ($p < 0.05$). See Table 3.2 for mean *d'* scores across SOA, Time and Group.

Table 3.2

Sound-Induced Flash Illusion: Mean and standard deviation (in parentheses) for the proportion of correct in the illusion conditions and d' score

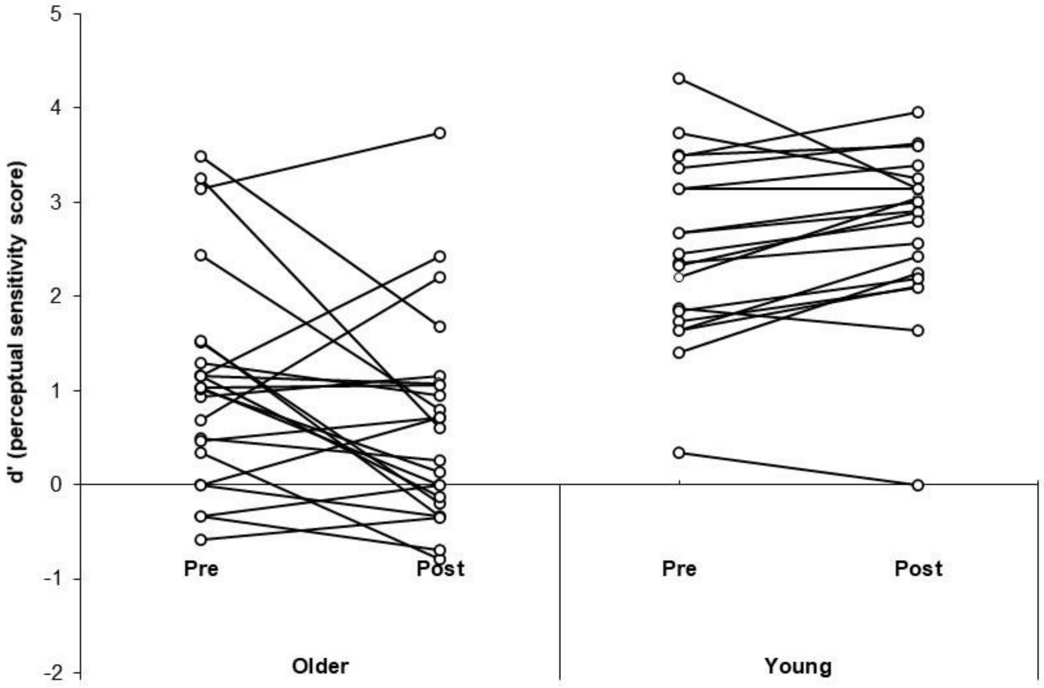
	Older	Younger
SOA	*M*	*M*
Pre		
70	0.42(0.36)	0.48(0.29)
110	0.33(0.4)	0.5(0.37)
150	0.27(0.33)	0.65(0.36)
230	0.27(0.32)	0.87(0.24)
Post		
70	0.39(0.24)	0.44(0.26)
110	0.19(0.27)	0.51(0.29)
150	0.23(0.28)	0.75(0.33)
230	0.3(0.31)	0.93(0.23)
d'		
Pre		
70	0.8(1.05)	1.5(0.89)
110	1.05(1.52)	1.93(1.47)
150	1.19(1.49)	2.78(1.71)
230	1.29(1.65)	3.75(1.25)
Post		
70	0.54(1.29)	1.22(0.88)
110	0.27(1.64)	2.15(1.31)
150	0.67(1.4)	3.44(1.44)

230	1.06(1.72)	4.01(1.47)

Performance was better than expected at SOA 110 ms (we anticipated lower sensitivity at all shorter SOAs relative to longer SOAs), which is likely due to the poor ability to discriminate the beeps at 110 ms leading to reduced illusions. There was a significant interaction effect of Time × Group [$F(1, 41) = 6.38$, $p = 0.015$, $\eta_p^2 = 0.14$]. Simple effects analysis (using paired samples t-tests) was used to follow-up the interaction effect. T-tests revealed neither the older [$t(22) = 1.99$, $p = 0.058$, $d = 0.41$] nor younger group [$t(19) = -1.95$, $p = 0.07$, $d = 0.44$] significantly changed in sensitivity from pre to post-training. The significant interaction effect was driven by the trends for reduced sensitivity post-training for the older group and improved sensitivity post-training for the younger group. Both trends approached significance in the t-tests, with medium effect sizes. See Figure 3.3 for a scatterplot of individual *d’* scores.

Figure 3.3

Scatterplots of individual perceptual sensitivity scores (d') pre- and post-training for the older adult and young adult groups



There was also a significant interaction of SOA × Group [$F(3, 123) = 10.63$, $p < 0.001$, $\eta_p^2 = 0.21$]. The interaction of Time × SOA was not significant [$F(3, 123) = 0.74$, $p = 0.53$, $\eta_p^2 = 0.02$] nor was the three-way interaction [$F(3, 123) = 1.65$, $p = 0.18$, $\eta_p^2 = 0.04$]. Considering the skew in variance, an additional 2 (Group) × 2 (Time) non-parametric ANOVA was conducted on *d'* scores. The main effect of Group maintained statistical significance [$F(1, 24.96) = 78.73$, $p < 0.001$]. There was no significant main effect of Time [$F(1, 24.51) = 0.11$, $p = 0.74$] nor an interaction effect of Time × Group [$F(1, 24.96) = 3.19$, $p = 0.09$].

Discussion

In this study, we aimed to utilize a paradigm that has been consistently successful with younger adults, simultaneity judgment (particularly the 2-IFC), to refine older adults' multisensory perceptual abilities. We also tested participants' performance in the SiFI pre- and post-training to assess the generalizability of any training effects. Three days of feedback training resulted in improved accuracy (i.e., greater percentage correct) on the 2-IFC task in older adults, with pre-training accuracy on average slightly better than chance (56%) and post-training mean percentage correct of 62%. As expected, the young adult group also significantly improved from a mean proportion correct of 73% at pre-training to 76% post-training. Furthermore, both groups experienced a significant narrowing of the TWI, indicating computer-based feedback training is effective for improving audio-visual discrimination abilities in both older and young adults. This is in line with previous studies which found similar effects in young adults (Theves et al., 2020). They found that this improvement is associated with increased beta-band oscillations post-training, compared to pre-training.

Of interest is whether this training effect generalizes beyond the 2-IFC task itself. For both younger and older adults, we did not find a generalization of training to the SiFI; participants did not significantly improve (i.e. reduce) their susceptibility to the illusion post-training. However, it is worth noting both groups showed trends approaching significance, such that the older group had a trend of reduced sensitivity post-training and the young group showed a trend of improved sensitivity post-training. The mean trend for young adults is in line with previous experimental research on this age group, where SiFI performance improved post perceptual training (Powers et al., 2016).

The observed trend for older adults showing decreased sensitivity after training is unexpected, considering their improved performance on the 2-IFC task. Fatigue may explain this finding, as the SiFI task was always administered last during post-training measurements, which occurred on the third day of a 3-day consecutive testing protocol. Attention is considered an important factor in multisensory integration (Talsma et al., 2010; Talsma, 2015) and attention has been found to modulate performance on the SiFI (Mishra et al., 2010). It is plausible that fatigue may have impacted older adults' attention during task performance, accounting for the trend for poorer performance post-training.

We argue the lack of generalization of training benefits for older adults could also be due to task difficulty of the 2-IFC task. While a significant narrowing of the TWI was found for older adults, many of the older group had the maximum window length of 300 ms (n = 19 at pre-training; n = 14 at post-training). This may indicate the SOA range was too short to capture a true reflection of TWI as several participants windows may have exceeded the 300 ms threshold. For example, Gieseler et al. (2018) in their study on older adults with mild hearing impairment estimated the average TWI at 70–220 ms for those who are not hearing-aid users and found enlarged windows for those who used hearing aids (TWI of 70–370 ms). While our study did not recruit individuals with mild hearing impairment and none of our participants were hearing aid users, it's possible older adults show considerable variability in their TWI and a greater range of SOAs is needed to capture this wide spread. The proportion of correct responses in the 2-IFC, even at longer SOAs such as 250 and 300 ms, was approximately 60–70%, indicating participants found the task challenging, although not impossible to perform. The average TWI reported with TOJ (Setti et al., 2014) was lower than 200 ms, suggesting a difference in task difficulty. Further methodological reflections should be highlighted, particularly when comparing the 2-IFC with the TOJ staircase utilized in previous studies (Setti et al., 2014). While SJs show narrower TWI in older adults compared to TOJ performance, with no age difference (for sound-lagging stimuli; Chan et al., 2017); the 2-IFC, specifically, requires one to maintain in working memory two pairs of stimuli and decide which one of the pairs was synchronous (or asynchronous). Considering that working memory capacity decreases with age (Wingfield et al., 1988), this task may produce a cognitive load that is difficult for older adults, as our older participants had close to chance percentage correct (56%) at baseline. The effect of training may be undermined by task difficulty; although some level of challenge is necessary for perceptual learning (DeLoss et al., 2013).

It is possible that a more tailored approach is needed, whereby the individual thresholds are established before starting the training and the SOAs are modified accordingly (see discussion on adapting stimuli to participant's sensory function in Hirst et al., 2020); alternatively a paradigm utilizing only one pair of stimuli (TOJ or SJ), i.e. potentially requiring lower working memory load could be more effective. Alternatively, it is possible that older adults, who rely more than young adults on previous knowledge in various tasks (Kathleen Pichora-Fuller, 2008; Maguinness et al., 2011; Chan et al., 2017), may show more limited improvements due to a decreased ability (or need) to update their implicit expectations, e.g. perceptual templates in such tasks. However, we propose that this is unlikely, considering that older adults have shown unisensory perceptual training abilities (e.g., tactile thresholds; Kalisch et al., 2008), and show a modulation of the SiFI, within participants, based on the number of SOAs, i.e., the information provided by the task. In addition, in the present study, a more comprehensive set of stimuli, including visual and auditory lead, could have offered more information to the individuals and, potentially, better training (see Chan et al., 2018). Finally, to account for possible lapses in sustained attention during training, a version of the SJ training like that of Yarrow et al. (2016) which offers the option of canceling trials due to inattention could be used in future studies. Canceled trials are repeated at the end of a trial block, therefore providing the possibility to participants of being potentially more confident about their judgments than in the present task. Further research is needed comparing such paradigms and the perceptual thresholds derived from them.

In their susceptibility to the SiFI, the present sample appears comparable to previous studies (Setti et al., 2014) with an average *d'* of 0.86 and 1, respectively. We found no effect of training in the susceptibility to the SiFI in young or older adults, but we note the young adults showed a trend for improved mean sensitivity post-training, a finding which approached statistical significance. The lack of an effect in older adults corresponds with previous research in the field, whereby perceptual training does not generalize to improvements in susceptibility to other perceptual illusions. The SJ (2-AFC) was not found to be predictive of susceptibility to the McGurk illusion in older adults in a lifespan study (de Boer-Schellekens and Vroomen, 2014; Stevenson et al., 2018). Similarly, SJ was not associated with susceptibility to the Stream Bounce illusion in Bedard and Barnett-Cowan’s study in older adults, while it was in younger adults (Bedard and Barnett-Cowan, 2016). Therefore it is possible that SJ training (2- AFC) generalizes to SIFI only in young adults, in line with the correlation found by Bedard and Barnett-Cowan (2016) between Stream Bounce and SJ in younger but not in older adults (but see Powers et al., 2016 for contrasting results). One result not in line with current literature is the better performance for older adults on SOA 70 ms compared to longer SOAs (i.e., they experience fewer illusions at SOA 70 ms). While this result counters our predictions as performance generally improves with longer SOAs, it can be explained by the poor auditory temporal resolution at SOA 70 ms in beep only conditions. It is plausible this reduced ability to detect auditory stimuli at SOA 70 ms could lead to reduced or non-experience of illusions. This result is also in line with recent findings on a sample of 3,955 individuals aged 50+ from The Irish Longitudinal Study on Aging (TILDA; Hernández et al., 2019). In this epidemiological study, participants were tested with a version of the SIFI comprising three SOAs; 70, 150, and 230 ms. Performance was significantly worse at 150 and 230 ms than 70 ms. However, while poorer auditory performance with an SOA of 70 ms can explain the lower susceptibility to the SiFI with the same SOA, the majority of participants are able to perceive the beeps and furthermore Gieseler et al. (2018) find older adults with mild hearing impairment show comparable susceptibility to the SiFI as normal hearing older adults of previous studies. Interestingly, amongst their sample of older adults with mild hearing impairment, they find greater susceptibility to the SiFI in hearing aid users compared to non-users, pointing to a complex association between hearing acuity and multisensory integration in aging (Gieseler et al., 2018). In light of this, the necessity of objective measures of participants' hearing acuity in future perceptual training studies with older adults is acknowledged.

While we could not register an effect of training on the SiFI, it is worth mentioning that, older participants' performance did not differ from the pre- to the post-training, supporting the claim that the SiFI is a useful tool to assess multisensory performance, robust to test/re-test for older participants.

As a limitation, we acknowledge that both fall-prone and non-fall-prone participants were included in our group of older participants, which may have led to additional variability in the overall findings, considering that fallers may have an extended audio-visual TWI (Setti et al., 2011; Stapleton et al., 2014). Further research is needed to discern whether perceptual training could reduce fallers' TWI and potentially reduce falls-risk. Another limitation of this study is the use of visual leading stimuli only. This choice is justified by Powers et al. (2009) finding that the TWI was more malleable with visual leading stimuli, likely because it was larger in the first place.

Considering that multisensory integration is emerging as a novel factor in determining cognitive and functional aging (Setti et al., 2014; Chan et al., 2018; Murray et al., 2018), it is of paramount importance to find ways to improve multisensory processing efficiency, when it is compromised by the aging process. In the present study we focused on temporal discrimination abilities. Perceptual training is the traditional way to improve temporal discrimination, we adopted a paradigm which was effective for narrowing the TWI in young adults to determine whether it is suitable for older adults. Although this is a pilot study, not a randomized controlled trial, we argue that the task-specific benefits of 2-IFC training for healthy older adults found here, should promote further research into the best ways to train temporal abilities across the senses in older adults, taking into account cognitive load. Furthermore, we note the large effect size found, with a post-hoc power of 99% (effect size f = 0.55) of the effect of training on 2-IFC performance. Future studies should also investigate whether working memory capacity is associated with 2-IFC performance in older adults, as we suggest here. At present, there is limited evidence of generalized perceptual improvement through training in older adults. It should be noted however that the present study presents SOAs up to 300 ms and visual-lead only stimuli. Although in line with previous literature, it is possible that exposing and providing feedback to participants on a wider range of SOAs could have led to improvements beyond the task itself (i.e. on SiFI performance). Whether a staircase procedure is necessary, although often more daunting on participants time and effort, also remains an open question.

The limitations of a small sample should be acknowledged; therefore, we cannot exclude the possibility that 2-IFC may lead to significant benefits for the SiFI or other multisensory tasks in a larger sample. However, our sample is in line with the sample size of published studies on young and older adults' perceptual learning. Importantly, we provide simultaneous data for young and older adults, allowing comparisons to be made in the outcomes of perceptual training for these two groups. Our research extends previous work on audio-visual perceptual training in younger populations (Powers et al., 2009, 2016; Theves et al., 2020) to older adults, providing evidence that 3 days of 2-IFC training can improve older adults' task performance and reduce their TWI, but this training does not generalize beyond the 2-IFC task (at least not to the SiFI task). We argue that the task-specific training results observed in this study are useful to inform future research to maximize benefits for participants in multisensory perceptual learning tasks, as ethical considerations should be taken into account before undertaking large trials with older adults, utilizing paradigms that have limited success in pilot work. This research contributes to mounting evidence that multisensory processing deficits in older adults' can be modified through targeted perceptual training. Perceptual training could potentially represent a novel intervention avenue for populations whose impairments are associated with underlying multisensory processing difficulties (e.g.

fall-prone older adults; Mahoney et al., 2019). Whether training produces benefits for functional abilities underpinned by multisensory processing (i.e. balance control) remains to be explored.

Data Availability Statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

Ethics Statement

The studies involving human participants were reviewed and approved by the School of Applied Psychology Ethics Committee University College Cork. The patients/participants provided their written informed consent to participate in this study.

Chapter Four: Study Two - Falls, Multisensory Processing and Physiotherapy-led exercise: An Exploration of Potential Links

Abstract

Multisensory integration (MSI) is fast emerging as an important factor associated with cognitive and functional impairment in ageing. Increased reliance on multisensory integration and increased susceptibility to perceptual illusions such as the Sound-induced Flash Illusion (SiFI) has been reported in fall-prone older adults relative to their healthy ‘non-falling’ peers. MSI may represent a novel intervention option for falls and a possible screening mechanism for predicting falls in older populations. Yet, little research has investigated the neural underpinnings of MSI differences in older fallers vs non-fallers and the impact of existing falls interventions on MSI functioning represents a gap in the MSI literature. Pilot behavioural and neurophysiological data was collected from 16 older fallers and 9 non-faller control participants. Due to the Covid-19 pandemic’s interruption to data collection, only exploratory analyses were possible, given the limited sample size. Preliminary analyses revealed older adults, both fall-prone and non-fall prone did not reliably experience the SiFI at a Stimulus Onset Asynchrony of 100 ms. Topographical plots of resting state electrical activity in the brain of older fallers vs. non-fallers were generated. This work provides important insights for future research on this population and this research topic. Methodological barriers were identified and include difficulty in recruitment and retention of participants, as well as difficulty in obtaining usable EEG data. The need for further research to explore the optimal SOA for inducing the

SiFI in an older population as well as age-related effects on reliability of the SiFI task in this sample were additional areas highlighted by this work.

Outputs

At the time of writing, this chapter reflects unpublished pilot work. The pilot data and experimental procedure have been presented at the following:

Setti, A., Chan, J., Cleary, M., O’Brien, J., & Dollard, M. (2019, September). *Falls, Exercise and Multisensory Processing: Using exercise training as a potential rehabilitation avenue for inefficient multisensory processing in fall-prone middle-aged and older adults*. Included at AFFINITY National Falls and Bone Health Symposium, Dublin

Setti, A., Chan, J., Cleary, M., O’Brien, J., Dollard, M., & McCullagh, R. (2019, November). *Falls, Exercise and Multisensory Processing: Using exercise training as a potential rehabilitation avenue for inefficient multisensory processing in fall-prone middle-aged and older adults.* Poster presented at Irish Hip Fracture Meeting, Dublin.

Setti, A., Chan, J., Cleary, M., O’Brien, J., & Dollard, M. (2020, October). *Falls, Exercise and Multisensory Processing.* Irish Osteoperosis Society Annual Medical Conference for Health Professionals, Trinity College Dublin.

Contributions

Jessica O’Brien was the lead author on this work, responsible for recruitment, data collection, data analyses and write-up of this work. Marie Dollard and Dr May

Cleary (Physiotherapy Department, University Hospital Waterford) facilitated participant recruitment, as did Ms Michelle McNamara (Senior Physiotherapist, Turners Cross HSE Falls Clinic). Marie Dollard assisted Jessica O’Brien with data collection.

Introduction

Falls is a leading cause of hospitalisation, disability and mortality amongst older adults (Kannus et al., 1999; Tinetti et al., 1988) and represents a major public health challenge, with falls costing the Irish economy €402 million each year (Gannon et al., 2007). In Ireland, up to 20% of falls in older adults are unexplained or described as ‘non-accidental’ (Davies & Kenny, 1996), leading research to search for unknown factors contributing to falls in older people. Mounting evidence indicates fall-prone older adults exhibit inefficient multisensory processing (i.e., a wider temporal binding window; see review by Zhang et al., 2020), a perceptual function underlying balance control and previously overlooked in its association with falls. Multisensory perception is the brain’s way of combining information from different senses into one coherent percept, allowing us to correctly perceive the environment around us.

Previous research indicates multisensory perceptual deficits characterise older fallers (Setti et al., 2011; Stapleton et al., 2014), with older fallers displaying poorer (i.e., less correct) performance on tasks of multisensory integration compared to their non-falling peers. A recent systematic review concluded that multisensory integration predicts falls in older adults (Zhang et al., 2020), supporting the emerging view that erroneous patterns of multisensory processing in older adults may contribute to functional impairments, including a heightened risk of falling (Mahoney et al., 2019). Current theories regarding the link between multisensory integration and falls posit the role of unisensory processing (Brooks et al., 2018; Hirst et al., 2019), attentional demands during postural control (Mozolic et al., 2008), inverse effectiveness (Laurienti et al., 2006; Mahoney et al., 2014), perceptual priors (Chan et al., 2021) and increased noise in the ageing brain (Mozolic et al., 2012). The role of age-related compensatory strategies has also been raised, with evidence older adults exhibit an enlarged temporal binding window for multisensory inputs (Bedard & Barnett-Cowan, 2016; Diaconescu et al., 2013; Diederich et al., 2008; Laurienti et al., 2006; Mahoney et al., 2012), whereby the timeframe during which sensory inputs are integrated is extended, potentially resulting in less accurate perception of their environment. The mechanisms underlying the link between balance, falls and multisensory integration remains equivocal, yet the evidence is undeniable that a link exists, opening a novel avenue for falls prevention and intervention.

Promising findings indicate multisensory processing is modifiable through training, presenting viable new options for rehabilitating fall-prone individuals. Recent research presents evidence that both computer-based perceptual training (e.g., Powers et al., 2009; Powers et al., 2016; Setti et al., 2014) and physical exercise (Holt et al., 2016; Merriman et al., 2015; O'Brien et al., 2017) are strong contenders for supporting multisensory perception in older adults, yet whether this is applicable to fallers remains to be tested.

Physical exercise or movement-based exercise is the current gold standard treatment for falls and falls-risk (National Institute for Health & Care Excellence, 2013). Multi-component exercise programmes, strength and balance training or Tai Chi exercise programmes are effective at reducing falls in older adults (Hopewell et al., 2018; Sherrington, Fairhall, Kwok, et al., 2020). Sherrington and colleagues found exercise programmes can reduce falls by 23% for older adults living in the community (Sherrington, Fairhall, Wallbank, et al., 2020). Along with a plethora of RCT studies, economic evaluations have also identified exercise programmes as a cost-effective approach to falls prevention and intervention (Davis et al., 2010). In

Ireland, the public healthcare system's (i.e., Health Service Executive (HSE)) primary intervention for falls comprises a programme of gait, strength and balance training, delivered either 1-to-1 or in a group setting by a Physiotherapist (Laffoy, 2008). Considering the wealth of evidence linking multisensory integration and falls in older adults, it is important to explore whether existing prevention and intervention approaches impact fallers' multisensory processing

To the best of our knowledge, no research exists which has explored the impact of public healthcare-run falls interventions on multisensory processing. Coupled with this is a notable gap in the literature with respect to the underlying brain mechanisms behind efficient and inefficient multisensory integration. Considering older fallers show different patterns of multisensory processing compared to non-fallers, evidenced by increased susceptibility to audio-visual illusions like the SiFI and enlarged temporal binding windows for multisensory stimuli, it is important to explore the neural underpinnings behind these differences. Existing research has pointed toward the important role of oscillatory brain activity in SiFI susceptibility, with gamma, alpha and beta implicated in a number of studies (see Hirst et al., 2020 for review). Pre- and post-stimulus gamma band activity has been correlated with SiFI susceptibility in younger adults (Kaiser et al., 2019; Mishra et al., 2007). Research has also identified patterns of neural activity prior to experiencing the SiFI, including increased beta band power in the left temporal gyrus (Keil et al., 2014) and reduced alpha power in the visual cortex (Lange et al., 2013). Less research is available on older adults, but recent work from Chan and colleagues (2021) reported stronger pre-stimulus beta activity in older adults compared to younger adults experiencing the SiFI, with the authors noting this may reflect a compensatory ageing strategy of relying on perceptual priors. Exploring potential differences in neural oscillations in groups more susceptible to the illusion could provide important insights into what underlies differences in multisensory integration efficiency. Another recent study used Electroencephalography (EEG) with older fallers to investigate oscillatory gamma and alpha activity during the SiFI (Scurry et al., 2021). The authors found reduced alpha power for older fallers on illusion trials (i.e., trials which induce SiFI) compared to non-illusion trials, a pattern which is thought to reflect reduced inhibitory control (Scurry et al., 2021). Fallers were also found to exhibit reduced phase amplitude coupling between gamma and alpha power in non-illusion trials.

Taking together two identified gaps in the literature on falls and multisensory processing, the present research aimed to explore the effect of 6 weeks of Physiotherapy-led falls exercise programme on multisensory perception in older fallers, using both behavioural and neurophysiological measurements. As 100 ms Stimulus Onset Asynchrony (SOA) is considered optimal for inducing the illusion (Shams et al., 2002), we aimed to explore the effect of training on SiFI performance at 100 ms SOA. Using EEG to capture resting state and in-task brain activity, we aimed to explore the neural underpinnings of training effects as well as compare brain activity patterns between fall-prone and non-fall prone older adults before and after the exercise programme.

Methods

Participants

Partial data collection was completed for this study; comprising of a sample of 16 fallers and 8 non-fallers. Faller status was determined by self-report of at least one fall in the past 5 years that required medical attention (see clinical guidelines in Todd & Skelton, 2004) and all fallers were currently accessing public healthcare outpatient services for their falls. Of the 16 fallers, 9 completed both pre- and post-assessments. 7 fallers completed pre-assessment only; 3 participants were lost at follow-up due to the Covid-19 pandemic and national lockdown in March 2020 and 4 were unavailable to complete post-test sessions (2 of the 4 cited health deterioration), leaving 7 participants. Age-matched, non-fallers (*n* = 8) were recruited as control participants and completed pre-assessment testing in order to provide a baseline comparison for performance on multisensory perception tasks and baseline brain activity. Only a subsample of control participants (*n* = 4) were tested before and after 6 weeks of community exercise classes (run by a Physiotherapist, involving strength and balance exercises). All participants were community-dwelling older adults living independently at the time of testing.

Fallers were recruited via the outpatient Physiotherapy Department at University Hospital Waterford (Co. Waterford) and at a HSE Daycare Centre for older persons (Turners Cross, Cork City). Control participants (i.e., non-fallers) were recruited through active retirement groups in Cork City and through snowball recruitment, whereby individuals who participated in the experiment informed their peers who may be interested in participating. Table 4.1 presents the participant characteristics for the sample.

Table 4.1

Demographic characteristics of participants who completed 100 ms SOA SiFI

	Fallers (*n* = 16)	Control (*n* = 8)
Age	77.45	70.6
Gender	62.5% female	75% female
Education level	Primary 50%, Secondary 41.7%, Third level or higher 8.33%	Primary 28.57%, Secondary 42.86%, Third level or higher 28.57%
Regularly use medication	93.75%	37.50%
No. of medications per week	37.69 (36.81)	8.13 (13.12)
No. of falls in past 5 years	1.75 (1.44)	0.13 (0.35)
SMMSE score	27.86 (1.41)	29 (1.07)
IPAQ score (MET-minutes)	941.86 (663.69)	2719.86 (1560.08)
TUG score	22.99 (10.3)	9.37 (2.12)
Falls Efficacy Score	7.81 (1.76)	10 (0)

Note. Mean scores presented (standard deviation in parentheses). SMMSE = Standardised Mini-Mental State Examination. IPAQ = International Physical Activity Questionnaire. MET = metabolic equivalents. TUG = Timed-Up-And-Go Task.

For fall-prone participants, additional measures included the Berg Balance Score (for those participants recruited and tested at University Hospital Waterford), administered and scored by a Physiotherapist (MD). The average Berg Balance Score was 41.63 (*SD* = 7.96) at pre-test for the subsample of 8 fallers and 41.2 (*SD* = 6.87) at post-test for 5 fallers.

Of the 16 fallers, 11 categorised their falls as accidental, 4 as non-accidental and one did not specify. The average number of falls in the past 2 years was 1.72 (*SD* = 1.36) for the fallers in this sample. Fifteen of the 16 fallers responded that their fall caused an injury. Fallers recorded their falls as occurring within the home for 7 fallers, outside the home for 1, out in the community for 5 fallers, in the home and outside the home for 2 fallers, in the home and out in the community for 1 faller. Three (18.75%%) fallers responded ‘yes’ to falling in the same place, 12 (75%) responded ‘no’ and 1 (6.25%) did not specify.

Fourteen fallers (87.5%) responded ‘yes’ to being afraid of falling and 2 responded ‘no’ (12.5%). Of the 14 fallers that reported being afraid of falling, 9 (64.29%) were ‘somewhat afraid’ and 5 (31.25%) were ‘very afraid’. Ten fallers (62.5%) responded ‘yes’ to the fall limiting their activities and 6 (37.5%) responded ‘no’.

All participants provided written informed consent prior to participation in the experiment. The study received Ethical Approval from UCC School of Applied Psychology Ethics Committee (University College Cork, Cork) and the Ethics Board of University Hospital Waterford.

Procedure

The desktop computer used to deliver all computer-based stimuli and tasks was a Dell desktop laptop (24-inch screen), with in-ear earphones (Etymotic ER-4SR) used to deliver the auditory stimuli.

Physiotherapy-led Group Exercise Class. Fallers were enrolled in a 6-8 week Falls Prevention class, delivered by a Primary Care Physiotherapist (fallers were required to attend at least 6 of the 8 classes). Classes were delivered in a group format with approx. Six fallers attended each class. The classes were held in the outpatient department of University Hospital Waterford. Classes were held weekly with each class lasting 1 hour and involved strengthening and balance exercises under guidance by the Physiotherapist. Four control participants were tested at pre-test only, but a another subsample (n = 4) were tested pre and post 6 weeks of Physiotherapist-led exercise classes delivered in the community. The Physiotherapist (falls specialist and working in a falls clinic), ran these exercise classes on a voluntary basis and adopted a similar programme to that used in the falls classes (i.e., strength and balance based exercises). Further data collection for this group was interrupted due to the Covid-19 pandemic and restrictions on group activities and experimental testing.

Outcome Measures

Demographic information. Participants completed a series of questionnaires including a demographic questionnaire, a Falls questionnaire (with items around their falls history), and a Modified Falls Efficacy Questionnaire (Hauer et al., 2010).

Participants' regular physical activity levels were assessed using the International Physical Activity Questionnaire Short Form (IPAQ-SF; Craig et al., 2017). The IPAQ has been validated on adults aged 18-65 (Craig et al., 2003). While not validated on older adults, it has been used extensively with older populations (see e.g.; Larsen et al., 2021; O'Brien et al., 2017). Participants' general cognitive ability was assessed using the Standardised Mini Mental State Examination (SMMSE; Folstein et al., 1975). Participants that scored below 24 in the SMMSE were not eligible to take part in this study. Participants' visual and auditory acuity was objectively assessed on a subset of participants (n = 8 fallers and n = 6 control) using the Etymonic Home Hearing Test and the Freiburg Vision Acuity Test (contrast sensitivity subtest only) respectively, both administered and recorded on the aforementioned desktop computer. Of the tested participants, all fallers and controls scored within the normal – mild hearing loss range (i.e., -10-40 *dB HL*; Clark, 1981). For contrast sensitivity, data was lost due to a technical fault, however as the visual stimuli used in this study are high contrast (i.e., white flash against a black background), this was noted as a minor limitation.

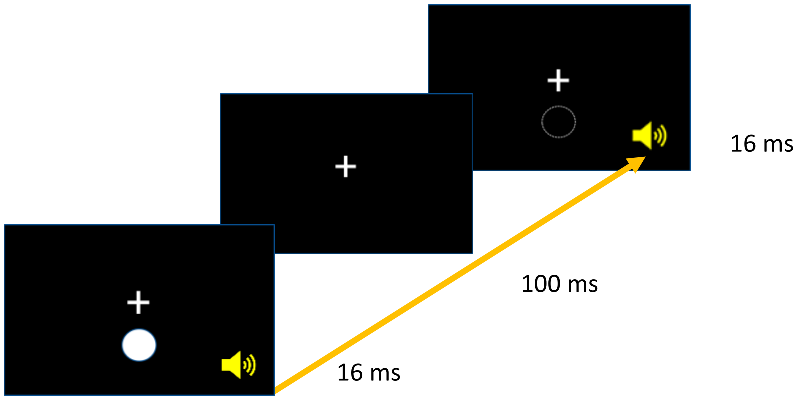
Balance Tasks. Participants' balance functioning was assessed using two tasks administered and overseen by a Physiotherapist; The Berg Balance Scale (Berg, 1992) and the Timed-Up-and-Go Task (TUG; Podsiadlo & Richardson, 1991). For the Berg Balance Scale, participants completed 14 movements of static and dynamic balance tasks, with the outcome variable being a participant's summed score across items, where 56 is the maximum score possible. For the Timed-Up-and-Go Task, participants were tasked to stand from sitting on a standard armchair (approximately seat height 46 cm and arm height 65 cm) without using the armchair arms or any physical assistance, walk at a comfortable and safe pace to a line on the floor positioned 3 metres away, turn, walk back to the chair, and sit down. Participants were timed in seconds on this task, with their time being their score on the task.

Multisensory Integration.

Behavioural performance. Participants' multisensory integration efficiency was assessed based on their performance on the Sound-induced Flash Illusion Task (SiFI; Shams et al., 2002). The visual and auditory stimuli for the SiFI were identical to those used in the experimental study outlined in Chapter 3 (please refer to Chapter 3 for specifications of the stimuli). Visual and/or auditory stimuli were presented for a duration of 16 ms on a black background. The Stimulus Onset Asynchrony (SOA) used in this experiment was 100 ms. Given the necessity for a large number of trials when working with EEG (i.e., due to potential artifacts in the data), it was decided to choose a single SOA that was likely to induce the illusion for all participants. 100 ms was chosen due to previous research finding greater integration at lower SOAs, e.g., Setti and colleagues (2014) found more illusions for older adults at SOAs less than 270ms, Chan et al. (2015) found older participants experienced illusions 60% of the time at SOA 100 ms. See Figure 4.1 for a visual representation of the SiFI stimuli and trial procedure.

Figure 4.1

Visual representation of SiFI stimuli during 1-flash/2-beeps trial



During the task, participants were seated approximately 50 cm from the computer screen. Participants were informed they would be presented with flashes and beeps and were instructed to count how many flashes (i.e., visual stimuli) they saw on each trial and to respond verbally. Each trial concluded with a response screen (a black screen with the text 'How many flashes did you see?') presented centrally onscreen. Participants were required to respond within 2000 ms of onset of the Respond screen or the next trial commenced. A research assistant (JOB or MD) seated next to the participant would then input the corresponding response onto the computer keyboard and initiate the next trial. A central fixation cross was presented on screen immediately before and after each trial. Participants were asked to attend to this cross throughout the experiment. Each participant received a practice block of 10 trials. This was followed by 5 blocks of experimental testing, to allow for breaks for participants during the task. Over the 5 blocks of testing, participants completed

425 trials presented in randomised order across these blocks. Between each block of trials, participants were offered a short break before continuing. Participants completed 175 illusion trials (1-flash/2-beeps) as well as control conditions of unisensory trials; 1-flash (100 trials), 2-flashes (50 trials) and 2-beeps (100 trials). As participants were always tasked with responding to the number of flashes, in the 2-beeps condition participants should respond 0 (i.e. zero flashes). The SiFI was programmed and administered using Presentation software (www.neurobs.com, version 18.1).

Electrophysiological recordings. A 128-channel active electrode EEG system (manufacturer: Brain Products, model: ActiChamp) was used to obtain data on participants' electrical brain activity. EEG recordings were taken for each participant in a quiet room on the outskirts of University Hospital Waterford. Two research assistants (JOB, MD) conducted the EEG set-up and testing. Preparation of the EEG equipment included placement of cap and addition of conductive gel (Supervisc electrolyte gel) to each electrode on the cap. EEG electrode positioning was carried out in accordance with the international 10/20 system (manufacturer: EasyCap; Oostenveld & Praamstra, 2001).

Resting-state EEG recordings were obtained for each participant for a duration of 10 minutes in total, during which participants sat with the EEG cap in place while completing the two baseline conditions of eyes-open (5 mins) and eyes-closed (5 mins), both while seated. In the eyes-open condition, participants were asked to look at a fixation cross. One research assistant sat on the left-hand side of the participant to deliver task instructions. A second research assistant monitored the EEG signals and EEG equipment throughout testing. (JOB and MD alternated these tasks during the data collection phase).

Approach to Analysis

Only participants that completed both the pre- and post-exercise testing were included in the analyses. For the SiFI, the variable of interest was participants' behavioural accuracy on the illusory condition (i.e., 1-flash/2-beeps trials). The dependent variable (i.e., accuracy) comprised participants' mean percentage of correct responses on these trials. Statistics Software SPSS (IBM; Version 23) was used to analyse the resulting behavioural data.

For EEG data, Matlab (version R2019b) was used to conduct statistical analyses and data visualisation using the EEGlab (Delorme & Makeig, 2004) and Fieldtrip (Oostenveld et al., 2011) open-source toolboxes. The first phase of pre-processing the data was completed using EEGlab. This included applying a high-pass filter at 1 *Hz* (recommended level prior to Independent Component Analysis; Klug & Gramann, 2021), filtering line noise at 50 *Hz* and associated harmonics (i.e., 50, 100 ,150 *Hz* etc.) and re-referencing to a common average reference virtual electrode. Following this, the data was imported to Fieldtrip where channels were visually inspected to identify potential noisy channels and artifacts in the data. Noisy channels were interpolated using the nearest neighbour method. Eye blink artifacts in the channels had been previously identified using Independent Component Analysis (Fast ICA) in EEGlab and muscle artifacts were identified using automatic artifact detection using z-score, followed by visual inspection and rejection methods in Fieldtrip (i.e., removing blocks in the data where artifacts are present).

After segmenting the data into 1 second epochs, Time Frequency Analysis (TFR) was then conducted on the data in Fieldtrip. First, in order to reduce the broadband artifact, a frequency-dependent Hanning window taper with Butterworth filter was applied to the data. Frequency ranges of interest were specified at7-12 *Hz*, 12-30 *Hz* and 30-70 *Hz* at 2 *Hz* steps to explore alpha band, beta band and gamma band activity respectively (band frequencies selected as in Scurry et al., 2021 and Theves et al., 2020). Next, a multi-taper frequency transformation was applied to smooth the frequency estimate at higher frequency bands (60 *Hz* and above) to avoid spectral leakage and over-sampling. The maximum trial length was rounded up to the nearest power score of 2. Power spectra were then computed based on the Fast Fourier Transformation (FFT) of the segmented data. TFR data were averaged across participants in each group (i.e., fallers, control) to generate a grand average per group per condition (i.e., eyes-closed, eyes-open) for each of the three frequency bands specified (alpha, beta, gamma).

Results

Behavioural results

Table 4.2 presents the mean percentage of correct responses to each of the SIFI auditory-visual, visual only and auditory only conditions for fallers and non-fallers. Of note, as participants were tasked with reporting the number of flashes only, accurate scores on the auditory only condition (2-beeps) reflect a participant responding ‘no flashes’ on those trials as opposed to correctly perceiving the number of beeps.

Table 4.2

Mean percentage of correct responses on each condition of SiFI task (standard deviations in parentheses)

	Fallers		Non-fallers	
	Pre (*n* = 16)	Post (*n* = 9)	Pre (*n* = 8)	Post (*n* = 3)
1-flash	81.97% (12.3)	79.25% (25.26)	79.53% (26.97)	77.83% (24.42)
2-flashes	90.61% (9.79)	92.81% (7.37)	93.57% (6.91)	98.67% (2.31)
2-beeps	81.81%(12.85)	83.44%(11.35)	86.64%(14.71)	93.08% (8.93)
1-flash/2-beeps	79.40% (28.4)	68.23% (34.69)	76.75% (31.94)	76.66%(19.99)

Visual inspection of participants' individual scores revealed the presence of two data points deemed outliers, both with respect to the illusory condition (1-flash/2-beeps). One faller scored 1.43% correct on the 1-flash/2-beep condition and 17.5% accuracy on the 1-flash condition at post-testing, despite having above 80% accuracy on both these conditions at pre-test. Similarly, another faller displayed 2.99% accuracy on the 1-flash/2-beep condition at pre-test (participant did not complete post-test). Given the small sample size, removing these two outlier data points changes the mean scores for the fallers on the 1-flash/2-beep condition, such that fallers mean accuracy would be 84.5 (*SD* = 20.44) at pre-test and 76.58 (*SD* = 25.65) at post-test.

As anticipated, both groups of participants displayed high accuracy levels in the control conditions (i.e., congruent unisensory trials). Independent samples t-tests revealed there were no baseline group differences on performance on any of the unisensory conditions (i.e., 1-flash, 2-flashes, and 2-beeps). There was also no significant difference between groups on performance on the illusory trials at pre-test (1-flash/2-beep condition), $t(23) = 0.21$, $p = 0.42$. Both fallers and non-fallers also displayed a high percentage of correct responses on the illusory condition at both pre- and post-testing. This reflects high accuracy on the illusion condition, indicating participants respond ‘1 flash’ when presented with 1-flash/2-beeps and in effect do not experience the Sound-induced Flash Illusion to a great extent during trials.

Preliminary analyses was conducted on the pre- and post-test SiFI data to explore trends in performance following 6-weeks of physiotherapy training. The limited sample size must be noted here (fallers, $n = 8$, control, $n = 4$) and the output is considered pilot data. Paired samples t-tests on pre- and post-test data was performed separately for each group, given the difference in sample size across groups. For fallers, the t-tests indicated no significant difference in percentage of correct responses to the 1-flash [$t(7) = 1.12$, $p = 0.15$], 2-flashes [$t(7) = 0.47$, $p = 0.33$] or 2-beeps conditions [$t(7) = 0.002$, $p = 0.5$]. For older fallers, there was a significant difference between the pre- and post-test in the 1-flash/2-beeps condition [$t(7) = 2.21$, $p = 0.03$, $d = 0.78$] such that there was a lower mean percentage of correct responses at post-test compared to pre-test. For the control group ($n = 4$), there was no significant difference in performance on the 1-flash [$t(3) = 0.38$, $p = 0.36$], 2-beeps [$t(3) = 1.56$, $p = 0.11$] or 1-flash/2-beeps condition [$t(3) = 1.05$, $p = 0.19$] from pre- to post-test. There was a significant difference on the 2-flashes condition from pre- to post-test [$t(3) = 5.07$, $p = 0.007$, $d = 2.53$] with control participants showing higher mean percentage of correct responses at post-test.

In order to explore the observed low susceptibility to the SiFI which was contrary to expectation, it was decided to test a small number of participants at a longer SOA on the SiFI. It was reasoned that 100 ms may be too short a temporal interval, leading to potential merging of the illusory flash with the presented visual flash or that the second beep was temporally too close to the first flash-beep pair and may not have been registered by participants. A limited subsample of fallers (*n* = 3) were tested with the same SiFI paradigm with the SOA adjusted to 230 ms. Mean scores would not be interpretable for such small numbers so individual participant means are presented in Table 4.3.

Table 4.3

Percentage of correct responses for participants who completed experiment at SOA 230 ms

	Non-faller A	Faller A	Faller B
1-flash	100%	95%	8.33%
2-flashes	100%	96.67%	20%
2-beeps	95%	95%	65%
1-flash/2-beeps	96.15%	92.56%	4.6%

Electroencephalogram (EEG) results

Following data cleaning and pre-processing, the final sample of usable EEG data was *n* = 5 fallers and *n* = 3 non-fallers. Table 4.4 presents the demographic characteristics for the subsample of participants whose EEG data was examined.

Table 4.4

Demographic characteristics for participant data used in EEG comparisons

	Fallers (*n* = 5)	Control (*n* = 3)
Age	76.67 (1.15)	65 (6.08)
Gender	100% female	66.67% female
Education level	100% secondary education	33% secondary education; 67% 3rd level+
No. of medications per week	4 (4.36)	0.33 (0.58)
No. of falls in past 5 years	1 (0)	0.33 (0.58)
SMMSE score	28.67 (0.58)	29.33 (0.58)
IPAQ score (MET-minutes)	977 (867.84)	2832 (1633.58)
Falls Efficacy Score	7.33 (1.76)	10 (0)
TUG score	18.54 (8.18)	10.23 (2.44)

Note. Scores expressed in mean values. Standard deviation in parentheses

It was noted both during experimental testing and when inspecting participants' individual EEG data that much of the data was confounded by spurious and frequent eye-blinks and muscle artifacts rendering many participants' data unusable for data analysis purposes. While it is possible to remove eye-blinks using Independent Component Analyses (ICA), facial muscle artifacts are relatively broadband and difficult to filter, particularly in higher frequencies (Hipp & Siegel, 2013; Muthukumaraswamy, 2013). Therefore, epochs of interest were removed when muscle artifacts were present. Given the final limited sample size (number of participants and trials surviving artifact correction), it was not feasible to run inferential statistical analyses on the data. Here we present resting state comparisons (i.e., eyes-open condition, eyes-closed condition) for fallers and non-fallers.

Data for both groups were analysed separately for the two resting state conditions of eyes-open and eyes-closed. Time frequency analysis was conducted on the two data sets, with the frequencies of interest set between 7-12 *Hz*, 12-30 *Hz*, and 30-60 *Hz* to explore alpha band, beta band and gamma band activity respectively. Topographical plots of the grand average data was generated for each group at each frequency range and are presented in Figure 4.2 for alpha frequencies, Figure 4.3 for beta frequencies and Figure 4.4 for gamma frequencies.

Figure 4.2

Topogrpahical plots for power spectra for alpha frequency (7-12 Hz)

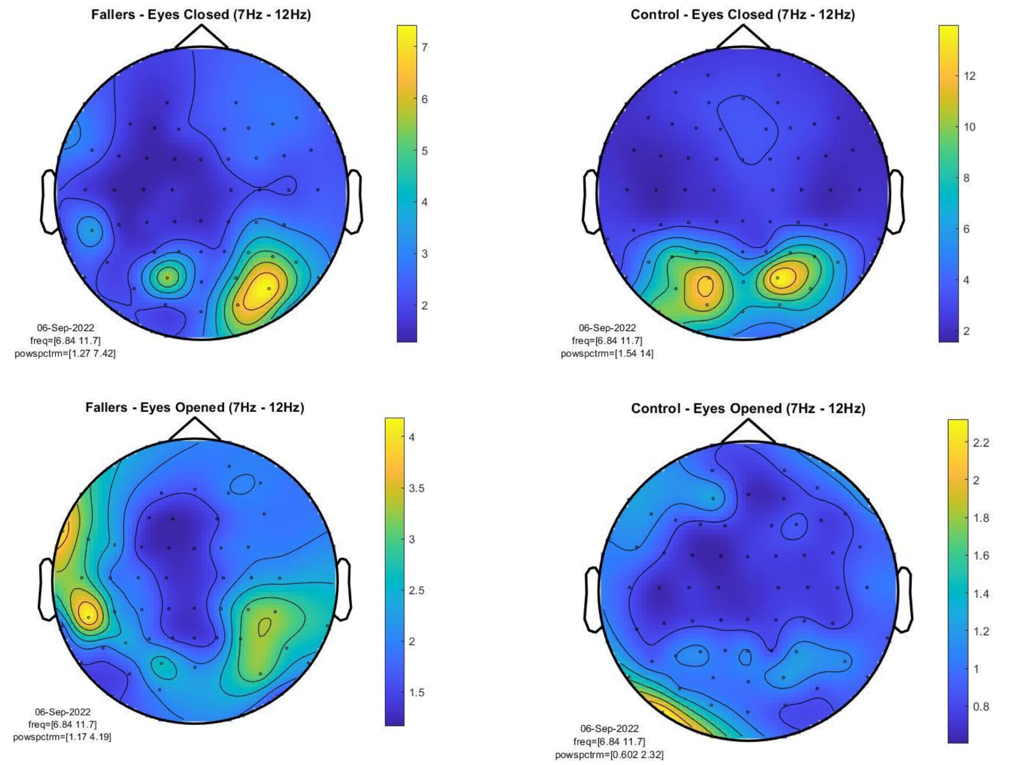


Figure 4.3

Topographical plots for power spectra for beta frequency (12-30 Hz)

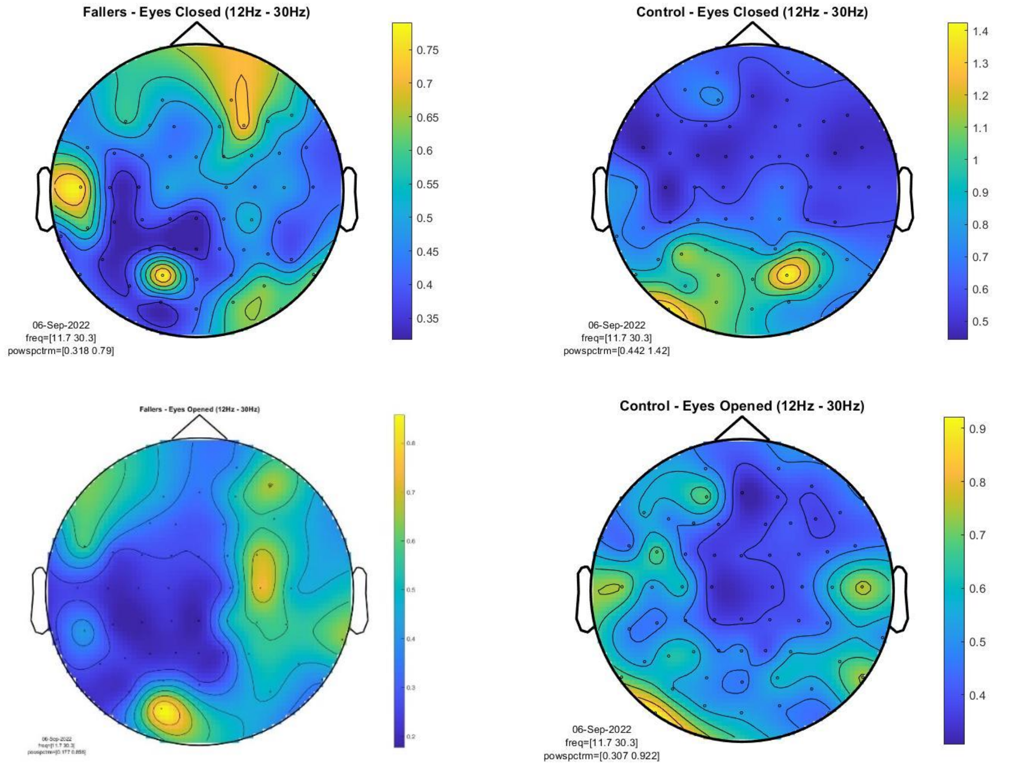
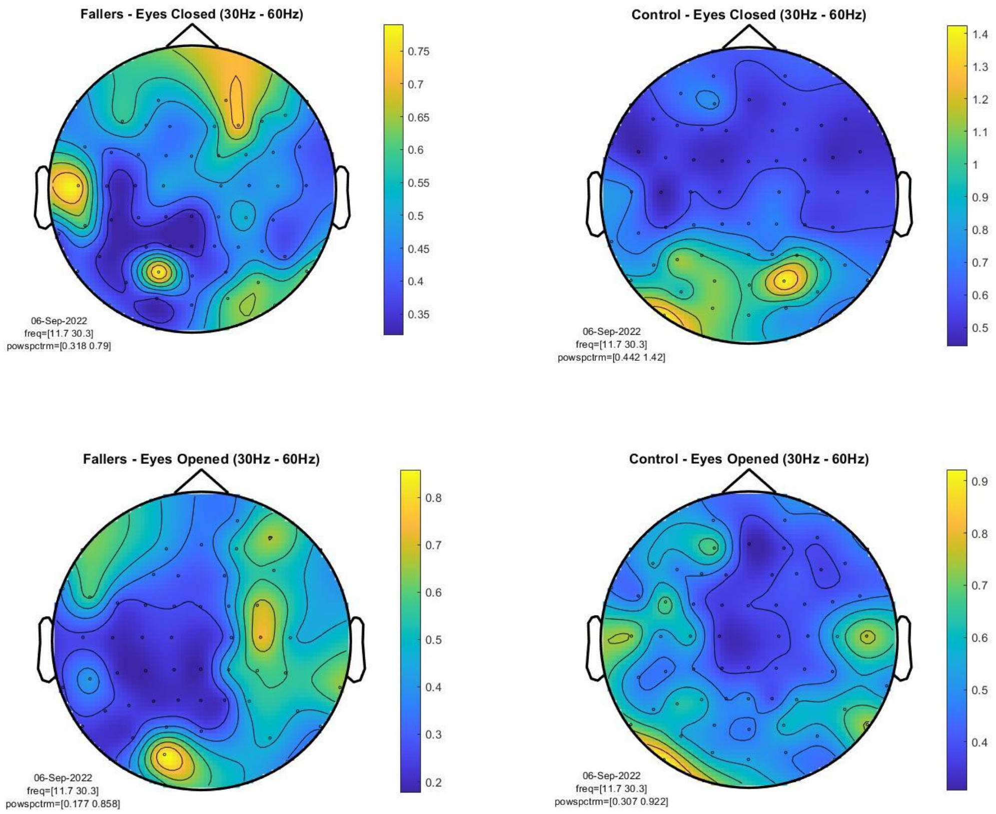


Figure 4.4

Topographical plots for power spectra for gamma frequency (30-60 Hz)



The presence of artifacts that remain in the data following pre-processing can be seen, for example the the high power seen for control in the eyes-closed condition in Figure 4.1 and both conditions for the fallers in Figure 4.1. The high power is localised to the occipital region in many cases, likely due to movement of the EEG electrode cables or electrode artifacts. (As the data represents pilot data, no inferences will be drawn from the power spectra plots, instead they represent the output that can be achieved using this study protocol.)

Discussion

The present chapter details research that aimed to address a number of gaps in the literature in relation to falls and multisensory processing. A growing evidence base indicates a link between falls in older adults and ‘inefficient’ multisensory processing. Yet little is known regarding the neural mechanisms underlying this link. Additionally, despite recent research exploring physical exercise and perceptual training paradigms as possible means to train multisensory processing (see reviews by Pinto et al., 2022; Zhou et al., 2020), no study has examined the impact of existing falls interventions, namely physiotherapy-led exercise on fallers’ multisensory processing. The present work, due to the testing restrictions during the Covid-19 pandemic, constitutes pilot data as experimental testing for this research could not be completed. Nevertheless, a number of insights have been gained from this work which may guide future research aiming to explore neural and behavioural effects of falls interventions for the fall-prone older adult.

Firstly, we turn to pilot behavioural data for our participants, who completed the SiFI task with illusory trials set to an SOA of 100 ms. Contrary to expectation, we see low rates of susceptibility to the illusion for both older fallers and non-fallers, with mean accuracy levels at pre-test being over 75% correct responses. This contrasts with some previous literature, where fall-prone older adults are found to be more susceptible to the SiFI compared to their non-falling peers (Setti et al., 2011; Stapleton et al., 2014). However, our findings are in line with those of two other studies, who found no difference in susceptibility between older fallers and non-fallers (Merriman et al., 2015; Stapleton et al., 2014). More surprising, is the high percentage correct found for all our participants, regardless of falls status. Previous research shows that while younger adults demonstrate susceptibility to the SIFI below 100 ms (Shams et al., 2002), older adults demonstrate higher levels of susceptibility to the SiFI at extended SOAs (e.g., 150, 230; DeLoss et al., 2013; McGovern et al., 2014; Setti et al., 2014). More specifically, Setti and colleagues have previously found older fallers and non-fallers scoring 25% and 56% correct respectively on SOA 110 ms of the SiFI (Setti et al., 2011), and Mc Govern and colleagues' found older adults experience the illusion ~40% of the time at SOA 110 ms (McGovern et al., 2014). The markedly greater accuracy for our group of older adults merits consideration.

It was previously thought that older adults show systematic decrease in susceptibility to the SiFI at longer SOAs, but recent work with a large sample size has found older adults experienced more illusions at SOA 150 and 230 ms compared to 70 ms (Hernández et al., 2019). The authors posited the 70 ms timeframe may be too rapid for the illusion to register (with older adults scoring over 60% correct at this SOA), considering a pattern of poor accuracy on unisensory performance at SOA 100 ms (see also Hernández et al., 2019). In the present study, we included a unimodal auditory response condition (2-beeps trials), participants were tasked with responding to the visual stimuli (i.e., respond zero as no visual stimuli). While this served to reduce the complexity of the task, it means we do not know if participants could accurately discriminate the auditory stimuli itself. We also could not collect measures of visual and auditory acuity for all participants, and therefore we cannot exclude the possibility that limited processing of the unisensory stimuli is driving participants' high accuracy on the 1-flash/2-beep condition. In effect, due to the speed of presentation of successive auditory and visual stimuli (i.e., 1-flash and 1-beep followed by 1-beep 110 ms later), the illusory effect (i.e., inducing a visual illusion) of the additional beep may not register. Hirst and colleagues recently found better visual acuity predicted reduced SIFI susceptibility in a large sample of older adults (Hirst et al., 2019). It is plausible that in our study using 100 ms SOA, we are seeing a similar effect as these previous studies finding better accuracy on the SiFI at low SOAs (often 70 ms). However, it must be noted that our participants displayed high accuracy on the included unisensory visual trials (1-flash, 2-flashes), indicating successful processing of the visual stimulus. It is evident that future studies utilising the SiFI should include control conditions to ensure accurate processing of the auditory and visual stimulus, which otherwise may represent a confound in the experiment.

The use of a singular SOA during the SiFI task presents a limitation of the present work and a consideration for future EEG studies of this nature. EEG research requires many more trials than behavioural experiments owing to the nature of the data being collected. However, using only a single SOA for the SiFI is problematic. One study has highlighted that the number of SOAs used in the SiFI affects susceptibility to the illusion, with younger and older adults showing enhanced susceptibility when fewer SOAs are presented (3 SOAs vs 5 SOAs; Chan et al., 2018). The authors suggest this is likely owing to the availability of additional information (i.e., more SOAs) against which to compare their own performance. Interestingly, susceptibility was only enhanced for SOAs beyond the 100 ms window. In the present work, we see low rates of susceptibility to the illusion at a SOA of 100 ms, which is contrary to expectation and previous work showing high rates of susceptibility to the illusion at the 100 – 110 ms time interval. Of note, in Scurry and colleagues' EEG study which assigned a participant to one SOA for illusory trials (either 30, 70 or 150 ms), similar unexpectedly low susceptibility was found, with fallers exhibiting ~75% mean accuracy on illusory trials at 70 ms and

~90% at SOA 150 ms (Scurry et al., 2021). Taking together the present work and that by Scurry et al. (2021), an important consideration for future research is highlighted. Given the individual variations in SiFI susceptibility (McGovern et al., 2014), as well as group differences in susceptibility at varying SOAs (e.g., older fallers vs non-fallers; (Setti et al., 2011), trialling participants' susceptibility to the SiFI at a range of SOAs and setting the SiFI task at an SOA which induces many illusions may be necessary, particularly for research using EEG. Estimates of an individual's TBW may not be sufficient, given the non-linear variations seen in older adults' performances at different SOAs.

A second insight from the present work pertains to the lack of existing research into the underlying brain activity behind the multisensory processing differences seen between fall-prone older adults and their non-falling peers. While the field of multisensory integration has seen a surge of research interest and output, this area remains underexplored, yet vital to our understanding of multisensory processing in ageing. Furthermore, as evidence mounts for the specific multisensory integration profiles of various neurodevelopmental and ageing conditions (see Zhou et al., 2020 for review), it is paramount to gain insights into the brain mechanisms underlying these processing differences.

While only limited analyses of the neural data was possible, there is recognised value in exploring resting state EEG oscillations for clinical groups (Babiloni et al., 2020). Resting state brain activity is related to the spontaneous neural activity (local field potentials in this case) that underlies a person's fundamental brain state and possible functional connectivity (Giacino et al., 2014; Stam et al., 2005). The aim of recording resting state was to examine if there were changes to this fundamental brain activity that was related to the exercise program.

Our study provides pilot data exploring resting state oscillations in fallers and their healthy (non-falling) counterparts. Considering the small sample size, it is not possible to draw concrete conclusions and no formal statistical analyses was carried out. Nevertheless, we present evidence for the value in investigating resting state EEG in fall-prone older adults, given the possibility of differences in their neural profile compared to their peers. The present sheds light on the challenges of using EEG technology with older adults, particularly frail individuals. The high dropout rate, necessity of long preparation time for EEG set-up and the level of artifacts and interferences present in the end data all reflect obstacles of note for future research aiming to conduct EEG experiments with this population. Contamination of EEG data is common when conducting research with older adults due to the prominence of motor, movement and chewing artefacts (Rowan & Tolunsky, 2003). In terms of data loss for the EEG component of the study, 11 of 16 participants' data was unusable (68.75%) and 5 of the 8 non-fallers data (62.5%) was unusable for analyses. This coupled with the effect of Covid-19 restriction on data collection (n = 3 participants lost to follow-up and cessation of data collection from February 2020), resulted in extensive data loss in this study. Regarding EEG data loss, field notes from our testing sessions noted our fall-prone participants were physically restless, with many making subtle movements or very slight rocking during testing. Interesting qualitative feedback from fall-prone participants as part of Chapter 5 showed many participants considered the EEG aspect of the study 'cumbersome' and 'awkward'. When asked for suggestions for improvement, most fallers pondered whether the data could be completed without the use of conductive gel. These qualitative insights point to older fallers' experience of EEG testing as physically uncomfortable. It is possible that being seated for long periods of time and being required to sit still were difficult tasks for an older faller and may contribute to the many artifacts seen in the EEG data. The use of portable EEG technology may be a consideration for future work, an option which has been used successfully with dementia patients with chronic pain to reduce participant burden and maximise data quality (Pu et al., 2021).

Conclusions

While the work presented here represents pilot data due to interference to testing during the Covid-19 pandemic, there is value in the insights we can garner from the research carried out. Our study adds to the evidence that older adults' (including older fallers) susceptibility to the SiFI is complex, with further research needed to disentangle the temporal thresholds at which the SiFI is likely to be induced in different subgroups of the population. Additionally, we highlight the practical challenges associated with EEG research with older fallers and call for greater research focus for this area. Specifically, the need to investigate the link between multisensory processing and existing falls interventions is raised and an experimental protocol to fulfil this presented, albeit without completion of data collection. As we begin to exit the era of Covid-19 and its deleterious effects on experimental testing, the link between multisensory processing, falls and exercise merits renewed research interest, as an area that represents high applied and societal value in addressing the public health challenge of falls amongst our older population.

Chapter Five: Study Three - Experience of Being Fall-prone and Participating in Research

Preface

The Public and Patient Involvement (PPI) element of research has gained prominence in recent years, with increasing recognition of the value and ethics of involving stakeholders and participants in research design and development. The aim being collaboration, where research is conducted *with* our participants, not *on* them (National Institute for Health and Care Research, 2021). The subjective experience of research for participants has often been overlooked. Evidence suggests PPI efforts dwindled during the Covid-19 pandemic (Murphy et al., 2020) and PPI efforts, while increasing, are seen as falling short in terms of producing meaningful inclusion of the public (Ocloo & Matthews, 2016). The personal experience of participants who engage in research has long been overlooked, and research in the area is in its infancy, with existing work largely confined to large-scale health and social care research (Maccarthy et al., 2019), with few PPI efforts focused on basic science and experimental research.

In the context of the Covid-19 pandemic and its impact on the ability to carry out experimental research with older adults, the opportunity arose to incorporate a PPI element to my research. With my core experimental work on hold, I was afforded the time and circumstance to complete qualitative work remotely with my population of interest; fall-prone older adults, and seek insights into their personal experience of participating in my doctoral research. The benefits of including participant voices in doctoral research has been highlighted, with the core aspect being exposing early career researchers to PPI, and in doing so, establishing the importance of capturing participant/service-user perspectives in research to avoid token PPI engagement (Troya et al., 2019). The following chapter details a piece of qualitative work exploring the personal experience and insight of participants (who partook in the experimental work outlined in Chapter 3).

Abstract

The importance of giving a voice to groups of individuals who are considered hard-to-reach for research purposes is becoming increasingly apparent, with insights into their experience having the potential to pave the way to improve research participation and outcomes for such groups. Fall-prone older adults are one cohort under-represented in research, often excluded in large scale research projects and are noted as difficult to recruit for research purposes. Understanding fallers' perspectives on research involvement represents a dearth in the literature to date. Thus, this study aims to explore older fallers' experiences of being fall-prone and participating in research. Seven fall-prone older adults (4 males and 3 females, aged between 69 and 88) took part in telephone interviews following their participation in an experimental research project. Semi-structured interviews explored participants' personal experience of being fall-prone and participating in research on falls, with data saturation reached by interview seven. The resulting data was analysed and interpreted using Braun & Clarke's thematic analysis (Braun & Clarke, 2006). Three primary themes emerged, each relating to different aspects of fallers' experiences of being fall-prone individuals and participating in research. Participants' accounts are captured under three primary themes: 'Research through the eyes of older fallers' and 'Living with Falls', 'It's all in the mind is it?'. Our research adds to the growing efforts and increased focus on involving hard-to-reach research groups in qualitative investigations to learn of their experiences and views on research. Our study gives voice to fall-prone older adults who have recently participated in an experimental research study to learn of their personal views on research participation and being fall-prone.

Keywords: fallers, research participation, public and patient involvement

Outputs

At the time of thesis write-up, this work is being prepared for submission to a peer-reviewed academic journal.

Contributions

Jessica O'Brien (JOB) is the lead author on this work. Marie Dollard (MD) and Dr May Cleary facilitated recruitment of participants. Jessica O'Brien and Marie Dollard jointly completed data collection. Marie Dollard supported with data analyses and reviewing codes. Write-up was completed by Jessica O'Brien. The work was supervised and reviewed by Dr Annalisa Setti and Dr Jason Chan. The qualitative analyses was reviewed by Dr Anna O'Reilly Trace (UCC).

Introduction

Falls represents a major public health challenge, with our global population progressively ageing and falls in older adults being one of the leading causes of hospitalisation and mortality. In Ireland, 1 in 3 adults aged 65+ experience a fall every year (Barrett et al., 2011). A fall can have debilitating effects for an older individual's physical and mental health, with physical injury and the associated psychological distress affecting quality of life for a faller (Moore & Ellis, 2008). The impact of a fall lives on beyond the fall event itself.

The causes of falls amongst older adults remains something of an enigma. Primary factors considered are physical frailty, environmental hazards, sensory decline and psychological factors, including fear of falls (Voermans et al., 2007). However, it is estimated 1 in 5 falls remain unexplained (Bhangu et al., 2016). A recent study using a large nationally representative sample (n = 4706) highlighted the complexity of falls, as despite measuring over 70 baseline risk factors for falls (including mobility, cardiovascular health and medication), they found low predictive accuracy for identifying future falls in community-dwelling adults (Donoghue et al., 2022). The authors also reported gait and mobility assessments did not accurately discriminate fallers and non-fallers. Furthermore, existing falls prevention and intervention strategies enjoy limited success (see Day et al., 2002; Fabacher et al., 1994), despite falls costing the Irish national health service (HSE) in excess of €160 million every year (Nolan et al., 2016). Extensive research has focused on the causes of falls, yet much of this work is quantitative in nature, with little existing research on fallers' own insights into what causes their falls.

Considering the importance of falls amongst the older population in terms of societal and economic cost and the fact older adults as a whole are considered a hard-to-reach population (Mody et al., 2008), it is surprising little research exists on older fallers' experience of participating in research given their importance yet inaccessibility as research stakeholders (see Berge et al., 2020). There is a growing realisation amongst the research world that giving voice to hard-to-reach participant groups could provide important insights into how to increase research uptake and participation for these subgroups (Baczynska et al., 2017; Marcantonio et al., 2008).

Existing qualitative research in this area has focused on fallers' experience of having a fall and their perception of falls risk (see synthesis by Gardiner et al. 2017). Giving voice to older fallers' experience of research participation serves several purposes. Firstly, fallers are considered a hard-to-reach population for research participation with recruitment amongst this population difficult. A qualitative investigation into fallers' perception of participating in research would provide insights into their barriers to participation and how to best accommodate their engagement with research studies. Furthermore, falls prevention initiatives see limited uptake (Nyman & Victor, 2012); understanding how older fallers conceptualise their falls could enlighten us as to why existing community programmes to support this group are not well attended. Finally, Randomised Control Trials (RCTs) and large scale research studies tend to exclude frail older individuals as a confound to a clean sample (Bourgeois et al., 2016). Including this often excluded patient group is an important step to begin to engage this population in the research process on ageing more broadly. Of the fallers that do participate in research, what motivates them to do so and how do they experience the process of participating in research? It is also important for us to understand what they expect as outcomes from their participation and what they would like their contribution to look like. Such questions are best answered by direct consultation with the participants themselves.

To our knowledge, no study exists on the topic of fallers' experiences of being involved in research, but a recent study investigated frail older participants' experience of research. Berge and colleagues (2020) explored frail older individuals' views on research participation, using grounded theory to explore their perspective on research involvement. In this study, frail older adults identified feeling they are contributing to society, and the social interaction with the research team emerged as motivating their participation. Challenging aspects of research involvement identified by the frail individuals included; doubts over their ability to provide a meaningful contribution to the project, and feeling like an outsider in terms of research activities (Berge et al., 2020). Berge and colleagues' (2020) overall theme of *challenging oneself on the threshold to the world of research* captures frail older adults' cautious interest in contributing to research despite doubts and personal challenges associated with research participation due to their frailty.

Given the similarities and at times overlap between frailty status and being fall-prone, it is plausible that there will be parallels in older fallers' experiences of being involved in research. Both frail individuals and fallers are often excluded from clinical trials (Ferrucci et al., 2004), are considered hard-to-reach populations and consequently, warrant research focusing on voicing their insights and experiences of research involvement.

A sample of older fall-prone adults who had recently participated in a falls prevention physiotherapy programme and subsequent experimental research project were included in this project. Participants were invited to a telephone interview post-participation to provide insights into their experience of being a fall-prone older adult engaged in experimental research. The aim of this study is to explore older fallers' experiences of participating in research.

Methods

Participants

Seven older adults, 4 male and 3 female aged between 69 and 88 (M = 79.83, SD = 7.73) participated in telephone interviews. Eleven potential participants were identified, three were uncontactable at the time of the study and a further one individual reported being unwell and unable to participate (currently in hospital for unrelated medical issue). The interviews focused on an individual's personal experience of participating in a research project conducted at University Hospital Waterford, Co. Waterford, Ireland. All participants had recently attended an outpatient Falls Prevention programme (group-based strength and balance exercise classes, 1 hour duration each, once per week for a total of 6 – 8 weeks) facilitated by the Physiotherapy Service at the Hospital. All participants are fall-prone older adults with a history of a recent fall and who receive outpatient care for the falls. Participants were living independently in the community at the time of the interviews, aside from one participant who had recently moved to a residential home. Table 5.1 presents the demographic characteristics for the sample.

Table 5.1

Participant Characteristics

	Value
Age mean (*SD*)	79.83 (7.73)
Female *n* (%)	3 (42.86%)
Education	Primary: 33.33%; Secondary: 66.67%, Third-level: 16.67%
SMMSE mean score (*SD*)	27.83 (1.17)
Berg Balance mean score (*SD*)	40.83 (9.24)

Note. *SD* = Standard Deviation, *n* = number, SMMSE = Standardised Mini-Mental State Examination

Procedure

Older adults who had recently attended a falls prevention programme and associated experimental research study (see Study Two in Chapter Three) were contacted via telephone and invited to participate in this research. It was explained to participants that this study was focused on their experience of participating in the research study as an individual who had experienced a fall. Of note, participants previously had also the opportunity to provide feedback about the research project following completion of the final experimental testing session.

For context, the experimental research study explored whether the falls prevention classes affected participants' balance control and a related perceptual function (audio-visual integration). The experimental study comprised two testing sessions pre- and post-attendance at the 6-8 week falls prevention class delivered at the Hospital. The testing sessions required participants to complete balance assessments (Berg Balance task (Berg, 1992), Timed-Up and Go task (Podsiadlo &

Richardson, 1991)) with a physiotherapist as well as demographic questionnaires. Participants also completed a computer-based audio-visual discrimination task (Sound-induced flash illusion; SiFI (Shams et al., 2002)) which provides a proxy measurement of multisensory integration efficiency. During the SiFI task, participants were presented with visual (flashes) and auditory (beeps) stimuli via a computer screen and were tasked with reporting how many flashes they saw on screen, while ignoring the beeps. While participants completed the SiFI task, Electroencephalogram (EEG) recordings were taken using an 128 channel EEG. This involved participants being fitted with an EEG cap and conductive gel was used on their scalp as part of the set-up process. Each testing session lasted between 3-4 hours, including set-up of the EEG cap.

Data collection

Telephone interviews were conducted in September 2020 during the global Covid-19 pandemic, when a national lockdown was in effect in Ireland (i.e., movement restricted to 2km from home, closure of all non-essential businesses, no visitors allowed to people's homes). Telephone interviews were the chosen method of data collection given the inability to collect data in person with a vulnerable group (i.e., adults aged 70+) during the pandemic. Telephone contact was chosen over video calls for ease of access. Two researchers (JOB, MD) coded the data simultaneously and reached a consensus on the definition and naming of themes.

The interview was semi-structured, with participants given the opportunity to respond to each of the questions on the interview schedule (see Appendix D), as well as allowing interviewers to explore other avenues of interest to the research question if brought up by participants. In light of the specific context during which the interviews took place, namely the global Covid-19 pandemic, Covid and the national lockdown were understandably a topic often discussed by participants during the interviews.

The interviews lasted between 10 to 30 minutes approximately. The length of the interview was based on how much participants wished to talk and share their experiences as a faller and as a research participant. Individual participant's memory of their participation also affected the duration of the interviews, with interviews shorter where memory of the research session was limited. All interviews were audio-recorded and transcribed verbatim using Microsoft Word online software. Following the principle of diminishing returns (Creswell & Creswell, 2003), data saturation was considered when no novel themes were found in subsequent interview data. This point was reached following seven interviews and agreed upon by both researchers (JOB, MD).

Data analysis

The software package NVIVO pro 12 was used to code and organise the transcripts. The steps of analysis progressed as follows and in accordance with Braun and Clarke's guidelines for thematic analysis (Braun & Clarke, 2006). Firstly, both researchers (JOB, MD) involved in the coding of the data, read and re-read the transcripts along with listening to the original recordings of the interviews. Initial coding was data-driven and completed on a line-by-line basis. The second stage of coding involved focused coding, with both researchers revisiting the initial codes and refining them in light of having read and coded all transcripts. Next, codes were grouped into categories based on their similarities in terms of addressing the research question around participants' experiences of being fall-prone and involved in research. These categories were then refined into themes and sub-themes with a theme being a pattern of responses that says something relevant to our research question. Direct quotes from participant interviews are used in the results section to capture their voices.

Researcher Reflexivity

Both interviewers took time to reflect on their position as researchers in this study and their differences when compared to the participants in this study. Age was considered the main distinguishing factor. Both interviewers are young researchers, while our participants are aged 69+ and classified as fall-prone individuals. Both interviewers were aware of their outsider role, considering their age and physical health. Both interviewers were also consciously aware of the possible power dynamics at play, given older adults' unfamiliarity with research activities and the fact the research was conducted under the auspices of the hospital which participants attend for outpatient care. Every effort was made to ensure participants understood their participation or non-participation in the study would not affect their level of care at the hospital.

Ethics

This study was approved by the Ethics boards in both research institutions involved in the project; School of Applied Psychology Ethics Committee (University College Cork, Ireland) and the Ethics Board at University Hospital Waterford (Code: 447597811662, Waterford, Ireland).

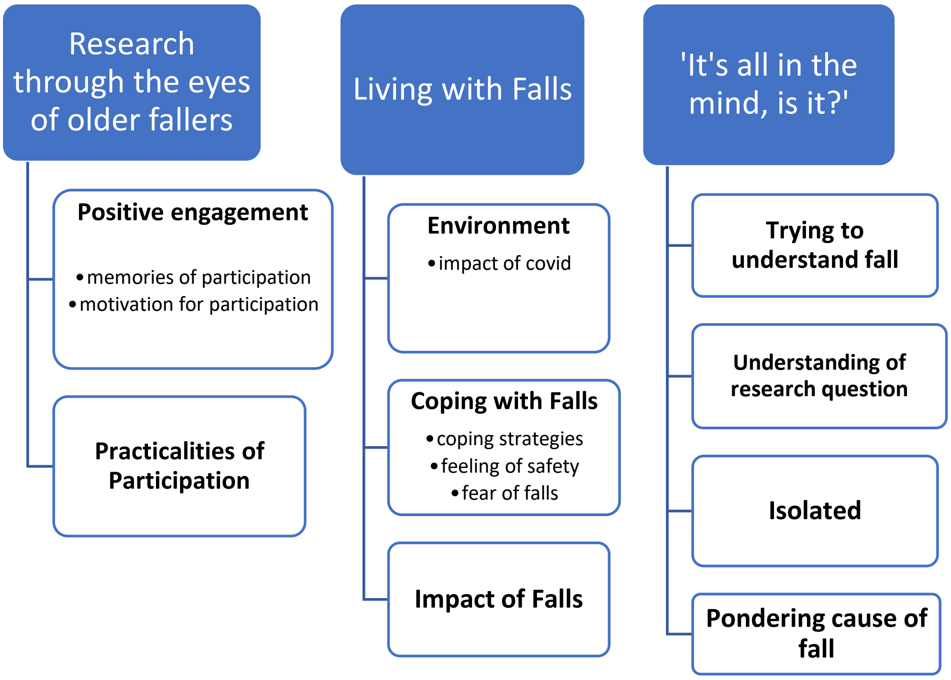
All participants had previously engaged with the researchers during their involvement in an experimental study of 6 weeks duration. Participants had provided written informed consent at that time. Verbal informed consent was established with participants at the start of the telephone interview. Participants were advised of their right to withdraw from the phone interview at any time without repercussion. Participants were all outpatients of University Hospital Waterford and so it was made clear to each participant that their participation or non-participation in the research interview would not affect their access to health or medical care at the hospital in any way. The researchers who conducted the phone interviews had both previously met participants at an earlier date for experimental testing as part of an earlier falls-related experimental study. Both researchers are skilled in working with older adults in a research capacity. All participants were assigned participant numbers (P1, P2 etc.) during the writing-up of the analysis to preserve confidentiality, pseudonyms were not used given the small sample size and risks of identification.

Results

Three interconnected narratives emerged from the participant interviews whereby participants spoke about their experience of life as a faller, of participating in falls-based research, and how they individually make sense of their falls. These narratives are captured in our three primary themes*; Research through the eyes of older fallers, Living with Falls* and *'It's all in the mind, is it?'.* Figure 5.1 depicts the primary themes and sub-themes captured in the interview data.

Figure 5.1

Themes and sub-themes from the interviews



Research through the eyes of older fallers

Fall-prone older adults are faced with unique challenges with respect to participating in research. Mobility difficulties, and falls-risk can lead them to restrict their movements and limit their opportunities for partaking in a range of activities, including research projects. When speaking about their experience of being a research participant, older fallers mentioned two core aspects; their positive experiences and their thoughts on the practical aspects of being a participant.

Positive engagement. The sub-theme of positive engagement comprises two categories related to participants' experiences; their memories of, and motivation for, participation in the experimental research study conducted at the hospital.

Memories of participation. During interview discussions, the majority of participants made reference to their limited memory of the specific events in the research sessions. It should be noted there was a considerable gap between research sessions and the post-research interviews, with between 6 and 16 months elapsed in between. Given participants' age, it is understandable incomplete memory of the research sessions was mentioned during interviews, as participants reflected on their experience of the experimental testing sessions. The following quote captures participants' incomplete recall of the sessions;

"I didn't think I did so well with them flashes [experimental stimuli], I don't know. I don't remember how I did or the specific details really" (P4).

However, all participants commented on the fact that what they do remember is that they enjoyed the research sessions. In particular, every participant referred to the social element of research participation, with most noting that social engagement with the research team was a positive experience and a memorable aspect of their time as participants. Participants made reference to the research team being "*lovely people*" (P2) and many stated their enjoyment of the conversation with the team, "*we had a bit of a laugh there*" (P1). A statement from one participant captures this enjoyment of the social element of being a research participant:

Ah it was ahm a trip out I guess. It was no trouble and I- as I said earlier it was nice to get out of the house and talk to you girls y'know. It was good for me (P4)

This is linked with the next theme, as the opportunity for social interaction during research participation was highlighted by participants as an aspect of the experience they valued. When reflecting back on their role as a participant, many fallers saw the social exchange during the research sessions as beneficial to them personally.

Motivation for participation. Participants were also positively engaged due to different motivating factors driving their participation. Motivation stemmed from a mixture of factors, including self-interest (personal enjoyment, seeking answers to questions), collective group interest (i.e., feeling of representing 'fallers') or for the common good (i.e., repay others who have helped them, repay society). In terms of their motivation for volunteering as a research participant, some fallers mentioned the feeling that they were contributing something important that would help somebody else. By way of an example, one faller mentioned they felt that by participating in this research project, they were giving back to society, referring to a previous fall incident where passer-bys assisted her and various healthcare professionals supported her recovery:

I suppose if I thought it would help other people or something, I don't really know. I think it's because I felt like I was doing something to make payback for all the help and attention I got when I broke my hip (P5)

Participants had a sense that they were helping others out by attending the research sessions, which contributed to their enjoyment of being a research participant. Participant 5 stated "*…the people who did it were lovely people. I felt I was helping people. It was nice, I enjoyed it".*

Others noted their experience of being a faller as a source of motivation for them to contribute to research exploring falls:

The fact, I was having the occasional fall like you know maybe spurred me to do it (P2)

There was a sense that as they were fallers themselves, contributing to this research project was on behalf of their group (i.e., of fallers), that they were representatives as such. Many participants echoed this, indicating that the research topic was of interest to them and so was personally relevant, resulting in their decision to take part in the study. Few of the participants made reference to the fact they were interested in the end result of research, hoping it would answer some of their questions in relation to falling. One participant hoped participating in all research opportunities they came across would eventually lead to a personal benefit for them in terms of dealing with a fall, stating "*I just want to know how to get up if I fall, that's all" (P1).*

Practicalities of Participation. As participants reflected on their experiences, they were probed for any feedback or suggestions for improving future older fallers' experiences of contributing to this experimental project. While many participants admitted to limited memory of the finer details of their participation, some aspects of the study were well-remembered by most participants and mentioned as suggestions for improving participant experience. Feedback centred around the practicalities of research participation, with some participants suggesting their desire and need for more instrumental support to facilitate their participation (e.g., improving the transport to and from the experimental sessions). The awkwardness and general dislike of the conductive gel used during EEG testing [participants wore an EEG cap during testing which involved conducive gel being injected onto their scalp] was mentioned by several participants as something to be improved or changed for future research of this nature. Many participants suggested that having a hairdresser would be an improvement, while others speculated at ways around the use of the gel:

Oh that's horrible, it's hard to get it [conductive gel] out. Had to wash my hair to get it out. If you could find some way of am doing it without putting that kind of gel on it, something else, oil or something that would come out easy (P4)

When it came to receiving feedback or results from the research, participants presented different views on this, with some expressing a keen interest in being provided with a summary of the study results and other participants stating they had no particular interest in being contacted or sent such information.

Living with falls

Living with falls is comprised of narrative threads which emerged around participants' status as fall-prone individuals and how they live their lives as fallers. The role of environments, coping with falls and impact of falls were all topics discussed by participants in relation to their physical status as a faller.

Environment. When asked about their experience of being a faller, many participants provided descriptions of recent falls they experienced, in particular focusing on the environments where they fell or felt likely to experience a fall. There was a general consensus amongst participants that being outdoors, navigating footpaths and steps, and moving location were scenarios identified as uncomfortable or *"tricky"* for them as fall-prone individuals. Each participant's fall experience was spoken about extensively during the interviews, highlighting how important a fall event is for these older adults. It was clear from the interviews, that for older fallers, feeling safe was dependent on a person's environment, with familiar environments bestowing a sense of safety. *"Anywhere not that familiar"* or most outdoor spaces were avoided by participants due to the perceived risk of falling in such places.

Interestingly, participants picked out specific aspects of an environment that they considered "*safe*" or "*comforting*" and this was quite individual to each person. For example, one participant in residential care found that having a bell to press was comforting for her, while another participant spoke about his own garden when asked about a place he feels comfortable in or safe (i.e., low risk of falling). Yet another participant pinpointed their own bed as the space they feel most safe in respect to risk of falling.

Coping with falls. Throughout the interviews, participants gave accounts of their lived experience of coping with being a fall-prone individual, at times providing tips as to how they manage and other times, explaining how falls have shaped aspects of their lives and their daily routines. Taking the collective experiences of our participants, two ways of coping emerge in their discourse; one being the use of physical aids and supports and the other being mental strategies or approaches participants have adopted in their day-today lives to manage their falls-risk.

In terms of physical coping strategies discussed by participants, a number of different aspects were highlighted as important for supporting their independence. For some, this comprised the use of a walking stick or frame or pieces of technology (e.g., help bell on wrist) or access to healthcare (i.e., a medical card). For others, people-based support was highlighted, including the support of a caring family, spouse or nursing staff. People were seen as providing both emotional support and physical support with managing their falls-risk and falls incidents. When discussing these supports, whether physical items or individuals who provide support, fallers highlighted their reliance on them, the necessity of these forms of support to allow them to live a meaningful and safe life despite their high risk of falling.

'Oh I'd be lost without it [walking stick]….I can't go very far at all without it (P2)

Yeah, I'm fine with her [cousin who is retired nurse]. I don't stumble or anything with her (P5)

The second strategy mentioned by participants was centred around a mindset or approach used to either minimise the risk of falls (avoidance strategies) or preserve their quality of life (involvement/active strategies). Such strategies were identified by participants as ways to help them feel more in control of their falls and their lives. Almost all participants described the need for them to "*be careful"* reflecting a cautiousness and vigilance around their risk of falling. One participant described it as *"I have to watch myself" (P6)*. Perhaps stemming from this cautiousness, some participants spoke of avoiding outings or occasions due to the perceived risk of falling. One participant explains her reasoning:

Like I don't go anywhere really y'know, I- I try and avoid going someplace now, because I don't go to funerals or weddings or ANYthing, y'know (P4)

While participants were not asked directly about their means of managing their falls, each participant spoke of ways they cope with being fall-prone during their discussions about living with falls. Participants' coping mechanisms for living with falls varied, but generally fell within the categories of having a positive mindset, keeping active and exercising caution in their day-to-day lives. Participants spoke about how "*you have to keep going" (P1)* and many fallers mentioned keeping active and moving as much as they could, representing an active approach, i.e., facing a falls-risk situation as opposed to avoiding exercise and movement; "*I don't vegetate" (P6)*.

An interesting aspect around coping with falls emerged in fallers' discourse during the interviews, whereby a number of participants spoke about the need to get on with their lives and not question or dwell on their falls. For some, this appeared to represent an internal coping strategy. Essentially, many of our participants gave a sense of accepting their fall-prone status and accepting that falls will happen, regardless of whether they adopted a more avoidant or active approach to events/occasions in their day-to-day lives (e.g., avoiding new situations or choosing to continue being physically active despite falls-risks). For many fallers, future falls were seen as a foregone conclusion. For example, one participant spoke of her belief that the government or healthcare providers could do little to help;

'What can they do for goodness sake?....I mean it's just one of these things isn't it' (P2)

The phrase *"it's just one of these things"* was stated by another participant and many others echoed this sentiment throughout the interview discussions. The sense that falls are an inevitable part of life for these individuals was a narrative that emerged in the interviews and it appeared for some, adopting an acceptance of falls and the likelihood of falling again was a means of coping with falls:

'If you fall, you fall like, that's sort of it really, nothing can be done, I don't think' (P6)

Impact of falls. The knock-on effects of having a fall was something brought up by almost all participants. Many spoke of specific physical injuries as a result of a fall, with examples such as "*cracked three ribs", "cuts on my hand"* and "*banged my head"*. Linking with the focus on physical damage from falls, one participant's advice for other fall-prone individuals focused on sharing her strategy of being prepared for the potential physical health consequence of a fall (i.e., the need for urgent medical attention); "a*nd always have a bag packed for the hospital, just in case" (P5).*

Beyond the immediate and often physical impact of a fall, it was evident throughout the interviews that falls also have other consequences for older fallers, namely the pervasive impact on their day-to-day lives. While not framed as an impact by many participants, but mentioned as their ways of coping with being fall-prone, many of their coping strategies appear to have an impact on their lives, particularly avoidance-based approaches used to cope with falls. For example, many participants spoke about avoiding outings or declining invitations to events in order to preserve their caution around walking in unfamiliar spaces.

To sum up, the majority of participants spoke of an acceptance of their falls as part and parcel of their day, with variations in how participants chose to manage or cope with their status of being fall-prone. Some spoke of an avoidance-based strategy, choosing not to venture to novel environments and not to attend events (e.g., weddings, funerals). Others' narrative focused more on remaining active and *'motoring on'* with their lives, despite their condition, highlighting their choice to stay physically active in their neighbourhoods and communities.

"It's all in the mind is it?"

Fallers spoke of their own take on their falls, i.e., their conceptualisation of what being a faller means and what sets them apart as a fall-prone individual. A sense of lack of control emerged when participants were asked to reflect on the cause of falling. The essence of this theme is captured in a quote from one participant, with their statement of a rhetorical question during their interview; *"it's all in the mind is it?" (P4).* This line embodies the two elements of fallers' response to what causes their falls; firstly, that the answer is elusive and the question is as such unanswered and secondly, fallers' belief that the mind and psychological processes have a part to play, albeit not a clear or obvious one. When describing accounts of their falls, each participant noted obstacles in the environment as possible external sources of their falls. Not having a walking stick, uneven surfaces and slippery flooring were common culprits identified by participants as plausible things in their environment that may account for their fall. Yet, when asked directly to consider why they think falls happen to them, participants provided more psychological explanations for being fall-prone. The *"mind"*, *"brain"* and *"it's all nerves"* were identified by participants as possible root causes for their falls. This speaks to a potential conflict in the mindset of the faller, where we get a sense they feel out of control physically, and when faced with no apparent reason for a fall, they identify aspects of their environment that could be at fault, possibly in an effort to normalise a fall. Yet, the conflict lies in the fact that fallers believe little can be done to prevent falls and most frame their *"habit"* of falling as being an issue of the mind, with a strong psychological element behind it. In their interviews, older fallers mention the contribution of these psychological factors, with references made to lack of attention (i.e., need for caution to avoid falls) and fear or nervousness of falling.

Many of the fallers in this study spoke to this psychological aspect of falls, showing they considered the mind had a role to play in causing and preventing falls. One participant framed this as a self-fulfilling prophecy:

If you think you're going to fall, you're going to fall (P1)

This sentiment was echoed by many participants who spoke of the role of fear and anxiety in contributing to a fall. One participant (P4) captured this link when they voiced "*I find if I get nervous, I fall". This ties in with the psychological ramifications of being a fall-prone individual that was captured under the theme of Living with Falls, where cautiousness was highlighted as a strategy for coping with falls. Participant 4 elaborated on their observation that nerves contribute to their falls-risk, describing it as *"a feeling"* to be managed;

I was in town with friends and if I get nervous about falling… As sure as anything, I eh start slipping and and I'm eh taking baby steps then trying to overcome the feeling (P4)

Most participants eluded to the evasive nature of what causes falls.

There must be something somewhere, yeah, but I can't put a finger on it (P3)

Falls are a multifaceted phenomenon with many different potential causes and this fact was echoed throughout the interviews, with participants speaking of their exasperation at fruitless efforts to identify causes for their trips and accidents, *"I can't find a reason"*, *"I really don't understand why it would happen"* and many referring to the sudden nature of a fall as something *"that just comes over me".* Fallers' search for reasoning behind their falls may reflect a wish or control over their situation and their status as a fall-prone individual.

It just happened before I knew it like I… was falling before I knew it (P7)

The final aspect of the mind in relation to falls, is how participants view themselves in their mind, particularly in relation to their non-falling peers. There was a sense from participants that being a faller isolated one from others; participants in their language isolated themselves from friends and families when they described their condition (i.e., being fall-prone). One participant spoke of this feeling of difference, reflecting a sense of being isolated from peers:

> *I don't know anybody who is like me. If a person falls, a friend now we'll say. It'll only be a once off thing, say. But I, I broke ribs twice (P4)*

Considering the lack of clarity on what causes falls in older adults, as well as the role of psychological factors in contributing to falls and their extended impact, it is little wonder fallers frame themselves as distinct from their peers as their condition is difficult to conceptualise themselves, let alone explain to others who do not share their experiences. This theme 'It's all in the mind is it?' captures the poignancy that surrounds fallers as they speak of their falls and how it is to live with being fall-prone. Fallers' accounts of their lives reference the inexplicable nature of falls and how to them, it remains an open question and they make do with mulling over "*why me"*, and pondering "*how did that happen"*.

Discussion

Falling in older adults is the focus of much policy and research efforts, given its impact on the individual wellbeing, quality of life, economic cost in terms of hospitalisation, healthcare needs and even mortality. Coupled with this is the fact fallers are often excluded in large-scale research trials and when included in the research scope, fallers can be difficult to recruit and retain. There is a lack of existing research into older fallers' experiences of being research participants. This study took the opportunity of interviewing older fallers who had participated in an experimental research project, in order to gain insights into their perspective of being a faller and involved in research. The interview data produced three primary themes related to participants' experiences, the first relates to research participation and the two others relate to the experience of being classified as faller; Research through the eyes of older fallers, 'It's all in the mind, is it?', Living with falls.

Through participants' descriptions of their views on and experience of being a faller and research participation on this topic, this study provides a number of key insights into fallers' mindset and conceptualisation of their falls, each with clinical implications. Firstly, participants emphasised the value of the social element of research participation as both motivating their participation and as a benefit they took from their time as a research participant. Fallers in this study spoke about research as motivation to get out of the house and the social interactions with research staff *("laughs*", "*chats with the girls [research assistants*]") were described by fallers as good for them and an enjoyable aspect of their research experience. This is important in light of the limitations to social activities and out of home activities in general expressed by most in the second part of the interview. One can infer that research participation is worthy of overcoming the tendency to avoid going to places.

Of note, all participants in this study referenced the social aspect of the study as a positive, and memorable for them. This ties in with recent findings from a study with frail older adults (Berge et al., 2020), where social interactions also emerged as a motivating factor for research participation.

The current study also informs on some obstacles or barriers to participation, for example travel to the research setting, the risk of falls when going to unfamiliar spaces/environments and the potential for this to impact on fallers' accessibility and their ability to contribute to research studies. These insights into what aspects of the experiment were perceived or experienced as challenging for participants were captured under the sub-theme of 'practicalities of participation'. Two aspects in particular were identified as challenging by many of the participants, one being transport to the testing centre, which may constitute a barrier to research participation for older fallers, and the second being the EEG conductive gel. In terms of transport, several participants suggested the study could be improved by providing transport to the research facility. Secondly, in relation to the experimental procedure, the only aspect of the protocol which was identified by all seven participants as challenging was the EEG conductive gel. Most participants voiced their preference for no gel to be used or an alternative to be considered for future studies (e.g., oil was suggested by one participant, another suggestion was electrodes which do not require gel). These findings highlight the need for further research into older people's experiences of EEG for research purposes, with participant experiences of EEG being an overlooked aspect in research (see Izdebski et al., 2016), with the limited qualitative work available focusing on user experiences of EEG for individuals with epilepsy (e.g., see Sivathamboo et al., 2022).

Taken together, these findings have implications for future research studies in terms of facilitating fall-prone individuals participation and enjoyment. It would be beneficial for future research studies to include opportunities for ample social interaction and a context favouring that for fall-prone participants to ensure a benefit for them, as well as ease of access e.g. by providing transportation. Additionally, other programmes or initiatives aiming to recruit fall-prone older adults may also benefit from ensuring a social element to their programmes in order to appeal to this cohort (e.g., falls prevention/intervention initiatives).

A second insight pertains to fallers' conceptualisation of their falls, specifically the finding that fallers speak of falls as inevitable and "*just one of these things*". This may partially account for the notable poor uptake in falls prevention and rehabilitation programmes (e.g., see Day et al., 2002; Fabacher et al., 1994), given fallers' view that the cause of falls is elusive and their perception that nothing can be done about them. This may reflect a position where further falls once one is a 'fall-prone', i.e. had one or more falls, are seen as unpreventable and therefore, participation in falls prevention initiatives may be seen as futile in the eyes of the fall-prone. Added to this is fallers' descriptions of their cautiousness of new environments and mobility in the community in general and this may represent a deciding factor in their decision to partake in programmes, whether of a research or falls prevention nature. However, research participation may also be seen as an outlet for fallers to engage with in order to clarify their doubts around their condition, in particular, their view of falls as a phenomenon of the 'mind'. This opens the question of whether the co-design of research and falls prevention programmes is required, whereby fallers would be consulted in the process of research to maximise recruitment and retention of participants, whilst also offering opportunities for social interaction in a safe low falls-risk space.

Finally, an interesting narrative thread emerged in the interviews, related to fallers' perception of their falls. Participants' discourse around falls represented a conflict, whereby fallers described their historic falls in terms of the environment they were in and all participants unprompted, identified potential external aspects that may have caused their falls (e.g., slippery floor, uneven ground). Yet, when asked directly about what they think causes their falls, participants in our study spoke of the role of the mind (i.e., one's own anxieties) and psychological factors in causing a fall. This is captured in the theme and rhetorical question voiced by one participant "*it's all in the mind, is it?*". This sentiment was echoed across many of the interviews and belies fallers' questioning of their falls as a possible psychological phenomenon. It is plausible this reflects an internal coping strategy, whereby a fall is normalised through identifying potential external factors to shoulder the blame for a fall. This could reflect a struggle for control, whereby fallers may feel out of control physically (i.e., unable to prevent a fall, at high risk of falling) and attempt to exert control mentally, by framing their falls in a certain light. We see through fallers' language, this normalisation of their experience, with falls described as "*just one of these things"*, and the need to *"get on with things".* Also probable, is that fallers seek internal causes for their fall event, blaming their own attention or anxiety around falling, with the mentality of if you think you'll fall, you will fall echoed across many of the interviews. Interestingly, fear of falling has become an area of research in its own right, capturing an individual's specific anxiety around experiencing a fall and is debated as a predictor or risk factor for future falls (see Lavedán et al., 2018).

Limitations

It must be noted that the participant group in the current study are limited to fallers who access healthcare for their condition, i.e., all participants in this study were current outpatients of a hospital. Therefore, the voices of fallers who do not presently access healthcare but who participate in research are not represented here as all our participants were recruited through the Physiotherapy Department at a public hospital. It is plausible that the experiences and views of other groups of fallers may differ to our participants. Secondly, our participants had engaged in an experimental project exploring a potential novel cause of falls (multisensory integration; for review see Zhang et al. 2020), perhaps reflecting their attitude that the cause of falls is not clear. Other fall-prone individuals may hold different views and attitudes regarding our research topic and how they conceptualise their falls.

It is noteworthy the time lapsed between completing of the experimental study and participation in the telephone interviews. For some participants, they partook in the interviews over a year after being involved in the experimental research. While this must be noted as a limitation of the study, we consider it a minor limitation as the focus of the interviews was on their overall experience of research as opposed to opinions about specifics of the research protocol. All participants were able to comment on their research experience and it is unlikely incomplete or partial memory of the experiment session/day affected the themes that emerged from this study.

Conclusion

The present study provides important insights into older fallers' view of research participation and being fall-prone. Considering this population are difficult to engage in both research and falls-based initiatives, whether preventative or intervention-based, hearing the voices and perspectives of older fallers offers us an opportunity to adapt our efforts to support them to participate meaningfully and fully in community healthcare initiatives and research. This will likely benefit both them and scientific efforts to expand knowledge on their condition, and by extension intervention and prevention efforts to reduce falls and its impact on the lives of our older adults.

Chapter Six: General Discussion

Taken together, this thesis presents research aiming to advance our knowledge of multisensory integration, a perceptual function emerging as an important factor in healthy ageing. This work hones in on an identified gap in the multisensory research field, namely how to begin to realise the applied value of this research area in the ageing context. A particular focus is on the relationship to falls, as an aspect of ageing where multisensory integration shows promise in terms of applying research to real world problems, with falls representing a recognised threat to successful ageing and more broadly, our global goal of supporting the older population as they advance in years. Four pieces of research are presented here, addressing whether multisensory processing can be improved through training; whether this can be empirically tested in an older population (particularly in fall-prone individuals) with well-established and novel methods (i.e., physiotherapy), and what are the experiences and ideas of fall-prone older adults on taking part in research and more generally, on being a faller. Specifically, following the general introduction of Chapter One, Chapter Two presents the first systematic review of the evidence on training multisensory integration, synthesising what we know to date about the question of whether we can train multisensory processing. The review finds training studies fall within two broad categories; psychophysics-based perceptual training and movement/exercise-based training. Most training studies have adopted the former paradigm, with many using in-task feedback to train audio-visual integration, simultaneity judgements or temporal order discrimination. In general, the review finds perceptual improvements following psychophysics training, with most studies reporting improved task performance following feedback training. Importantly, the review concludes that the evidence remains equivocal around transfer of benefits beyond the task trained, with conflicting findings reported in the literature and heterogeneity across outcome measures and training paradigms used. The review also highlights the second strand of training approaches which are emerging in the literature; exercise or movement-based training. Exergame balance training (Merriman et al., 2015), chiropractic care (Holt et al., 2016) and regular physical exercise (O'Brien et al., 2017) have been explored for their potential benefits for multisensory integration. While the limited number of studies is noted, the findings are promising, pointing to physical activity (in a broad sense) as a possible ecological approach to train multisensory processing. The implications of this finding will be discussed at a later point in the discussion.

The systematic review is followed by two original pieces of experimental research; one experimental training study (Study One) and one study protocol for evaluating the effect of Physiotherapy-led exercise classes on multisensory integration and balance in older fallers (Study Two). Study One builds on the findings from the systematic review, which highlighted the relatively few training studies targeting older adults. Study One outlines an experiment that demonstrates a perceptual training paradigm successful with young adults is also effective for older adults, with perceptual narrowing (i.e., reduced TBW width) observed after 3 days of training (O'Brien et al., 2020). The study found training benefits did not transfer to susceptibility to the SiFI, raising questions about generalisability of training benefits to other tasks, even if related to the trained task. It had been expected that training would result in reduced susceptibility to the SiFI, as had been reported in previous work using a similar paradigm, albeit at a longer training duration (5 vs 3 days training; Setti et al., 2014). Given that transferability of benefits seems limited or absent, more research is needed to design apt protocols with the aim to reduce falls-risk. The second experimental study is presented in Chapter Four (Study Two) and details pilot data and a study protocol for exploring the effect of a current public healthcare intervention for falls (i.e., Physiotherapist-led exercise) on multisensory processing, using both behavioural and neurophysiological outcomes. This was an ambitious study, designed in collaboration with a hospital physiotherapy and orthopaedic department (University Hospital Waterford) involving recruitment and data collection with fall-prone outpatients of the department. Experimental set-up and testing was conducted on hospital grounds to facilitate outpatients' participation and to maximise retention during the study. This work was impacted by the Covid-19 pandemic, which necessitated the cessation of all experimental testing with individuals deemed at risk during the pandemic (i.e., adults aged 65+). While data collection for the study is incomplete, a number of important insights were gathered during the design, data collection and analyses completed on the pilot data. These will be discussed later in this chapter. Finally, a complementary qualitative investigation encapsulating the PPI element of my research is presented in Chapter Five (Study Three) and offers insights into older fallers' experiences of being a research participant and their thoughts on their condition. Telephone interviews with 7 older fallers who participated in Study Two yielded three central themes related to their experience of participating in a multisensory research experiment; Living with falls, 'It's all in the mind, is it?' and Research through the eyes of older fallers.

Each piece of work contributes to the growing field of research on the role of multisensory processing in ageing, an academic area where Ireland maintains strong research interest and input. The first nationally representative study to include a measure of multisensory integration (i.e., the Sound-induced Flash Illusion) is currently being undertaken here (The Irish Longitudinal Study on Ageing (TILDA);

see Hirst et al., 2022). The work presented in this thesis adds to this literature, providing experimental and qualitative insights on an Irish population.

Drawing together the findings from each of the Chapters presented here, a number of insights and contributions to the research field are drawn. These each relate to and fall under the overarching goal of beginning to realise the applied potential of the field in the form of insights or challenges we face in this respect. Psychologists have been tasked with actualising the applied value of our discipline (Miller, 1969) and the field of multisensory integration, while multi-disciplinary, is a prime example of this goal. The need to focus our efforts within multisensory research to move toward seeing the clinical value of the field and its application to real world problems has been highlighted as a major gap in our knowledge (see Barnett-Cowan, 2018; Meyer & Noppeney, 2011). In the context of ageing, recent work has made in-roads into the clinical-translational value of multisensory integration, specifically its diagnostic potential for falls (Mahoney et al., 2022) and mild cognitive impairment (MCI: Murray et al., 2018), yet multisensory integration also has potential in intervention and rehabilitation efforts, despite relatively little research tackling this applied avenue. Two questions are posed by this thesis, and insights gathered, in order to contribute to a field ever-growing and offering so much potential value for our ageing population. Can we train multisensory integration, a function known to be subject to age-related changes and associated with cognitive and functional decline? And secondly, if so, how should we go about bridging the gap between the existing literature and applications to real world problems, such as the public health challenge of falls amongst our older population.

The effects of aging on the human brain are well documented, with structural and functional changes evident with advancing age. Cerebral aging is a multi-faceted phenomenon, with cell atrophy and pathology associated with old age (see Rossini et al., 2007). Pathology in the form of neurofibrillary tangles and amyloid plaques are seen in both the healthy aging brain and the dementing brain (Rossini et al., 2007). This raises the question of individual differences in functional ability in spite of age-related brain pathology and molecular changes. The concept of cognitive or brain reserve has seen considerable research interest, with accumulated neuronal reserves as a result of genetics, lifestyle factors (physical activity, diet) and environmental factors (e.g., education, cognitive stimulation) leading to preserved function in old age despite cell atrophy (Koen & Rugg, 2019). Compensatory strategies to circumvent functional decline have also been researched, with reorganisation of neural networks and alternative neural strategies (Rossini et al., 2007) seen in older adults. Of relevance to this thesis are findings that training-induced expertise in specific cognitive areas are associated with decreased neural activation (Cabeza et al., 2018). This is thought to reflect an acquired cognitive reserve, raising the possibility of training-induced benefits in specific neurocognitive functions prone to decline with aging. Multisensory integration is one such domain, given its association with functional aging and risk of falls. The prospect of developing a reserve to preserve optimal multisensory processing is promising, given the rate of falls and the cost of falls-related disability in our older population (see Gannon et al., 2007).

Multisensory Integration is Trainable

Multisensory integration is important due to its link to cognitive and functional ageing. Specifically, multisensory integration is known to change over development (Noel et al., 2016; Stevenson et al., 2018), such that older adults are seen to exhibit extended integration patterns, which has been linked to poor global cognition (Hernández et al., 2019), poor mobility and greater risk of falls (Setti et al., 2011; Zhang et al., 2020). The value in this finding is in the potential application of this knowledge to create prevention or intervention strategies to improve individuals' lives and reduce adverse outcomes such as cognitive decline, reduced mobility and loss of independent living.

The systematic review of Chapter Two collated and evaluated the evidence for the effect of training studies on multisensory integration in neurotypical adults. While two recent publications include a synthesis of the effects of multisensory training programmes (Pinto et al., 2022; Zhou et al., 2020), this is the first systematic review of the evidence base. The review provides an important marker of the knowledge we have gathered to date and the gaps needed to be addressed in future research endeavours in order to move closer to developing an effective and usable intervention for refining multisensory integration. The systematic review found that training multisensory integration is possible and both traditional perceptual training paradigms (i.e., psychophysics tasks, often with in-task feedback) and movement-based training have been found to be effective. The review also uncovers that most existing training studies have used young adult samples, who arguably already exhibit optimal integration.

Considering the U-shaped development of multisensory temporal integration, young adults display the narrowest TBW (Noel et al., 2016; Stevenson et al., 2018), meaning their integration patterns are closest to true simultaneity (i.e., most accurate) relative to their younger and older counterparts. Conducting training studies with older adults and other groups who could benefit most from refining imprecise integration (e.g., large TBW) should be our prerogative. Yet, few training studies targeting multisensory integration in older adults exist. Indeed Pinto et al. (2022) in their recent critical review of multisensory integration training programmes for older adults highlighted this dearth in the literature. Our own systematic review, which has a broader scope (by including all healthy adult populations and any training studies including an outcome measure of multisensory processing), identified just 8 training studies including older adults in their sample, with much variation in the training paradigms used across studies. The question of whether existing trainings that have been effective in training younger people will also be successful for older adults is paramount. While the case may be made that training paradigms should be trialled on young adults before recruiting older samples (e.g., considering participant burden), the difference in integration patterns between the two age cohorts (see Basharat et al., 2019; Murray et al., 2016; Parker & Robinson, 2018) renders findings on young adults less relevant for those of us interested in training multisensory processing in older adults.

Recent work, including the original research presented in Chapter Two (Study One) has begun to address the need for training studies recruiting older individuals (McGovern et al., 2022; O'Brien et al., 2020), with young adults serving as controls in order to compare age-related differences in pre- and post-training performance. Our study replicates a successful training paradigm used with younger adults (Powers et al., 2009; 2016; Theves et al., 2020) on an older population. In the context of the potential value such training paradigms may hold for older populations and others who show less accurate multisensory processing, it is important to ensure the promising findings reported with groups of young adults, who display narrow perceptual processing are possible with these groups. In terms of healthy ageing, considering early evidence of audio-visual temporal disruptions in a number of neurodegenerative conditions (see Zhou et al., 2020), including mild cognitive impairment (Chan et al., 2015), Parkinsons' disease (Lewald et al., 2006) and pre-clinical Alzheimer's disease (Festa et al., 2013; Festa et al., 2017), novel training approaches that target multisensory difficulties observed in these conditions is a merited line of future enquiry.

Transfer of Training

A related point, is the issue of training generalisability, one that was highlighted in both Chapter Two (systematic review) and Chapter Three (2-IFC training study). Importantly, and contrary to expectation, Study One found training on the 2-IFC Simultaneity Judgment task did not generalise to improved performance on another task, the Sound-induced Flash Illusion. This finding is reflected in the systematic review (Chapter Two) where the issue of generalisability is raised, considering equivocal findings regarding transfer of training benefits in the training studies. Taking the SiFI as the measure of generalisability of training (the most common measure used in the training studies reviewed), conflicting results are highlighted by our systematic review. Some studies find transfer of training to SiFI susceptibility, while others do not. One of these studies is Study One, our 3 day Simultaneity Judgement training with older adults, where SiFI performance did not change following training (O'Brien et al., 2020). Since publication of Study One, a recent piece of experimental work has found 2-IFC training transferred to reduced susceptibility to the SiFI for both young and older adults (McGovern et al., 2022). Mc Govern et al. (2022) also employed a 3 day 2-IFC Simultaneity Judgement training and so the contrasting results are worth reflecting on. Mc Govern et al. (2022) used a broader range of SOAs on the SiFI (25 - 400 ms), where we used shorter ones (70 - 230 ms) and in light of the high accuracy often observed at short SOAs compared to longer SOAs (i.e., 70 ms; Hernández et al., 2019; O'Brien et al., 2020), this may point to the effect of SOA selection on the results. It is plausible that our shorter range of SOAs were too narrow to capture training benefits, which may have occurred at longer SOAs, where asynchrony judgements should be easier to discriminate. This is noteworthy for future studies using the SiFI or other task of audio-visual temporal integration in order to minimise the impact of potential methodological confounds on results.

Reviewing all studies captured in the systematic review, there is an indication task difficulty is a factor at play in the transfer of training benefits. The small number of studies and the heterogeneity in outcome measures used precludes any broad conclusions to be made, but several studies included the SiFI as a measure of near transfer and comparing these studies offers us some insight. A pattern emerges where training studies which use increasing complexity of trials (or staircase procedures) report transfer of training benefits to SiFI performance (McGovern et al., 2022; Setti et al., 2014), whereas studies that do not systematically adjust task difficulty see no transfer of training to SiFI susceptibility (O'Brien et al., 2020; Powers et al., 2016; Zerr et al., 2019). Additionally, two other studies where training involved increasing difficulty lead to transfer of training to other multisensory tasks or stimuli (McGovern et al., 2016; Sürig et al., 2018). This represents early evidence that merits further study in order to begin to formulate the optimal training type to induce multisensory benefits with maximum likelihood of transfer. A parallel may be drawn here to the cognitive training literature, where the sweet spot of training difficulty has been noted, with optimal training tasks being those that challenge the trainee, but not to an extent where they are insolvable and frustration may set in

(Green & Bavelier, 2008). Considering the accumulating evidence for the role of task difficulty in training transfer, there may be value in the use of tailored training approaches, whereby individual perceptual thresholds are measured prior to training and training stimuli and SOA modified to optimally challenge each participant (see Hirst et al., 2020).

In terms of physical exercise and the potential mediating role of task difficulty, the limited number of exercise-based training studies including an outcome measure of multisensory perception precludes much commentary here. Only four studies utilising either physical exercise or movement-based training paradigms were identified by the systematic review. However, it is noted that multisensory benefits were observed for a traditional physical exercise protocol over an exergame balance training. Furthermore, our work investigating the impact of an acute exercise bout on SiFI susceptibility found differential effects of different modalities of physical activity in older adults and children (O'Brien et al., 2017, 2021). Open-skill exercise (which may be defined as more cognitively demanding, e.g., group-based exercise such as aerobics) resulted in reduced SiFI susceptibility, whereas a less cognitively stimulating exercise (lane swimming or individual gym use) did not (O'Brien et al., 2017). This finding was framed around theories of cognitive stimulation, whereby activities (such as physical exercise) with high cognitive load promote greater cognitive gains compared to less cognitively demanding ones (see Pesce, 2009). As open-skill exercise requires rapid updating of movements in response to random external stimuli (mirror sequence of movements of dance instructor), this represents a mode of physical activity with high cognitive demands. In contrast, closed-skill exercise is seen as less cognitively stimulating as it is self-paced with less requirement to adapt one's actions due to a relatively stable and predictable environment (e.g., repetitive swimming strokes). Considering different physical exercise types, the role of arousal levels (i.e., exercise intensity) should be considered in light of evidence of differential benefits of different exercise intensities on cognitive functions (see e.g., Chang et al., 2012; Lambourne & Tomporowski, 2010). While our previous study represents only one piece of research and is limited by its quasi-experimental design, it nonetheless raises the question of task difficulty or the level of stimulation during exercise as a factor to consider in terms of training efficacy and generalisation.

Drawing on the cognitive training literature, which is a more mature literature in the ageing field, with similar aims as multisensory research, i.e., to train specific brain processes through laboratory derived training protocols, we reap some lessons. Doubts around generalisability or training transfer has dominated the cognitive training field, with consistent evidence that training does not lead to benefits beyond the task trained (i.e., no far transfer; see Melby-Lervåg et al., 2016; Stojanoski et al., 2018). In the multisensory research field, as can be seen from the synthesis of training studies in our systematic review, near transfer is limited. Conflicting evidence for training benefits to untrained perceptual tasks is inconclusive. Take for example transfer to speech perception, Zerr et al. (2019) found 1 and 3 day Simultaneity Judgement training (2-AFC) lead to improved speech perception post-training, measured using the Word Recognition Test. Yet, De Niear and colleagues (De Niear et al., 2018) trained two groups on a simultaneity judgement task using simple stimuli (flash-beep) or speech stimuli for 4 days, using feedback as the training mechanism. De Niear et al. (2018) found training did not transfer to performance on the task if the stimuli differed from those trained, i.e., training on flash-beep stimuli did not lead to benefits for the task using speech stimuli.

While it is promising that some training studies have documented transfer of training benefits to untrained tasks, the presence of findings that contrast and do not show transfer of training are important. They raise the question of applicability of our research, as training task performance is of little applied value to an issue like falls, if training benefits do not transfer beyond the trained task, especially because it is unlikely that it will transfer to outcomes associated with real world functioning. Our systematic review also highlights the lack of clinical outcome measures included in existing training studies, with most using task performance and a second distinct perceptual task to measure training transfer. While this is methodologically sound and provides insights into the mechanisms behind multisensory processing, it is imperative that the multisensory training literature now focuses its efforts on ensuring future research explores the impact of training on clinical outcomes and other dependent variables relevant to real world scenarios. In the case of falls, the impact of training on balance measures, gait and fear of falls would be important indicators of future falls-risk. These were measures we included in Study Two, in which real world applicability was central. While completion of this study was not possible due to pandemic restrictions, it nevertheless provides an insightful framework for the direction future research exploring training multisensory integration should go; to include clinical measures associated with physical health and functional ability.

Training Mechanisms

The evidence points to the malleability of multisensory functioning, both in terms of the alterations in multisensory integration and the TBW across development; and our finding that older individuals’ performance on multisensory tasks is modifiable through training. An important line of enquiry for future research is to uncover the mechanisms of the observed training benefits, especially considering the two divergent lines of training studies; psychophysics-based training and physical exercise.

First we turn to the traditional paradigm used for perceptual training, computer-based psychophysics experiments, which have seen much interest since early work by Powers and colleagues (2009) found an individual's performance on tasks of audio-visual simultaneity judgements could be modified through feedback training. Many of the training studies that followed (reviewed in systematic review) adopted variations of the trainings reported in the Powers studies (Powers et al., 2009; Powers et al., 2016), often using trial-by-trial feedback to train participants' task performance. Trial-by-trial feedback is thought to promote rapid acquisition of the presented task, leading to improved performance with practice. This type of training is direct, using the same stimuli in the training paradigm as in the outcome measure in order to induce perceptual learning. Perceptual learning refers to 'long-lasting changes to [the] perceptual system that improve [the] ability to respond to [the] environment and are caused by this environment' (Goldstone, 1998), with the mechanisms of learning thought to include attentional reweighting, stimulus imprinting, differentiation and unitisation.

The mechanisms underlying physical exercise-induced benefits for multisensory integration are less clear. The benefits of physical exercise for cognitive functions is well documented (e.g., see Ratey & Loehr, 2011), but the impact on perceptual processes is underexplored. Evidence has linked physical exercise to efficient sensory integration (Prioli et al., 2005) and visual-somatosensory integration (Mahoney et al., 2014). Research from the physical therapies indicates physical activity may mitigate the effects of age-related alterations to sensory systems, including visual, somatosensory and vestibular functions (Shumway-Cook & Woollacott, 2007). As motor control requires recruitment of multisensory processes in order to navigate our surroundings and execute actions, it likely represents an ecological training of multisensory integration. Furthermore, multisensory integration underlies balance control (Bronstein, 2016) and physical exercise can have beneficial effects for balance maintenance (Lam et al., 2018; Pellicer et al., 2017). Of note, multisensory exercises (i.e., exercises which specifically target multisensory integration processes by simultaneous stimulation of two or more sensory modalities) have been found to benefit balance in fall-prone older adults. Despite these links between multisensory integration, exercise and balance documented in the literature, the potential underlying mechanisms remain underexplored, with some proposals being advanced (e.g., see Chan et al., 2021; Mahoney & Verghese, 2018; Paraskevoudi et al., 2018; Setti et al., 2011) and needing further exploration. The study protocol we present in Chapter Four outlines an experiment designed to address this gap, by including both behavioural and neurophysiological measures of multisensory integration as well as balance assessments in a study designed to explore the benefits of strength and balance training for fall-prone older adults. We believe the mounting evidence for multisensory benefits from physical activity warrants detailed investigation, with a particular focus needed on underlying mechanisms, considering the limited insight into this to date.

Novel Rehabilitation Route: The Case of Falls

Promising efforts to bridge the research-clinical divide have been made in relation to the potential diagnostic and screening uses for multisensory integration tasks. One of these relates to the public health issue of falls in older adults, where novel approaches for rehabilitation and early detection are actively sought. One laboratory group (Mahoney et al., 2022) are in the process of validating an iPhone app to capture multisensory reaction time in order to assess falls-risk. Computer-based psychophysics stimuli have been adapted for use on an iPhone as opposed to the usual laboratory-based computers in order to be accessible in community, clinic and other healthcare settings, including an older individual's home. The goal of this research being to provide an accessible user-friendly assessment tool for use by physicians to detect multisensory integration difficulties in older individuals who may be at risk of falls and to initiate falls prevention. This represents important work aiming to bring laboratory-based findings into practice within healthcare services. A second piece of research by Murray and colleagues (2018) outlines work with older individuals with MCI, where multisensory processing performance correctly discriminated MCI diagnosis, highlighting the potential diagnostic and intervention applications of multisensory tasks. These recent studies both point to the exciting prospect of what multisensory research and tasks could offer in terms of real world uses.

How to Move Forward: Insights into Methodological Barriers

A second related contribution of our work pertains to the methodological challenges associated with conducting translational-clinical research with older fallers. Study Three documents a study protocol for exploring whether Physiotherapy-led falls classes lead to changes to multisensory integration, both at a behavioural and neural level. Furthermore this study included clinical and functional outcome measures such as standardised and clinically-used balance measures (Berg Balance Scale) and falls-risk (i.e., Timed-Up-and-Go task). One of the main insights of this work is the obstacles in terms of conducting this research with older individuals, particularly frail or fall-prone participants. Implementing this research raised the following issues of note: recruitment, data quality and appropriate multisensory outcome measurements, even in the better case scenario of no Covid-19 pandemic. First, in terms of recruitment, Study Two involved collaborating with a public Hospital in another region of Ireland (Co. Waterford) in order to recruit fall-prone participants as efforts to recruit individuals in the local vicinity proved unsuccessful. Insights from the interviews with fallers who did participate highlighted the challenges a fall-prone older individual faces in terms of research participation. Transport issues were mentioned by some participants as a barrier to their engagement with research activities, but many also spoke of their feeling of safety in familiar environments and their strategy of avoiding unfamiliar places as part of their way of coping with being fall-prone. It is possible the recruitment drive in Co. Waterford was more successful as the testing occurred on hospital grounds, in a building participants would be familiar with as outpatients of the Falls service (although it was made clear that the study was independent from the care they received there). This is an important reflection and may explain some of the difficulties encountered in recruiting fallers to attend testing sessions at University laboratories. Interestingly, recruitment was less successful when testing was offered in a community Falls Clinic (Cork City); it is possible the hospital environment conferred more of a sense of safety in terms of dealing with a potential fall or other issue during testing.

Secondly, Study Two involved the use of EEG to capture neurophysiological markers of multisensory integration while participants completed the SiFI task. However, the magnitude of artifacts, including motor artifacts lead to many of the participants' data being unusable for analyses purposes. There are a number of possible explanations for this. One being based on the observation during EEG testing that older fallers made small movements when seated, and while subtle, would constitute artifacts in the data. Regular movements could be related to the duration of testing (approximately 3 hours), necessitated by the need for EEG set-up (e.g., electrode placement, application of electrode gel etc.) and the often slower pace of experimental testing required with older individuals to ensure comprehension and comfort with the testing procedure and experimental tasks. Complementary qualitive feedback from the participants during their interviews for Study Three (Chapter Five) highlighted older fallers' views of the EEG testing procedure, with many noting the gel (conductive gel) and 'cap' (EEG cap) as their least favourite aspect of the experiment and several participants speculated whether another method could be used to gather the same information.

Finally, the third point here relates to the outcome measurement of multisensory perception. In Study Two, we used the SiFI task with participants whilst measuring EEG activity. The study adopted a singular SOA (110 ms), chosen based on past literature showing reliable perception of the illusion at short SOAs (Setti et al., 2011; Shams et al., 2002). However, our preliminary findings show that older fallers and non-fallers (i.e., the control group) do not reliably experience the SiFI at this SOA, with low susceptibility to the SiFI found for both groups. While this is contrary to our expectation, it is in line with the only other EEG study that has explored the SiFI with older fallers (Scurry et al., 2021). Scurry et al. (2021) also find unexpectedly low susceptibility to the illusion condition. They utilised a number of SOAs but each participant only completed a single SOA in order to collect sufficient trials for EEG analysis, with the SOA varied across participants. Although based on previous findings from our lab (Chan et al., 2018), we would expect the inclusion of fewer SOAs (e.g., greater susceptibility to SiFi when using 3 SOAs vs. 5 SOAs) to lead to increased susceptibility to the SiFI, the opposite was observed in these studies of the SiFI using a singular SOA. However, specific findings in the literature also point to the role of unisensory processing (see Hernández et al., 2019; Hirst et al., 2019) and the possibility that participants did not register the illusory flash or the auditory stimuli required to induce the illusion.

Study Two, which despite being unfinished due to Covid-19, reflects a framework for the next steps in translating multisensory research into applications. We argue there is a need to explore existing interventions commonly used for populations who are now emerging as presenting with multisensory processing difficulties. In relation to falls, it is plausible that existing interventions for falls target multisensory processing, indirectly or inadvertently perhaps. In Ireland, Physiotherapy-led strength and balance exercise classes are offered to fall-prone individuals identified in the public healthcare system. Considering research highlighting the link between multisensory processing and balance control (see Bronstein, 2016; Zhang et al., 2020), such programmes may already benefit multisensory processing. For example, our previous work finds more precise multisensory integration (i.e., reduced SiFI susceptibility) following a single bout of physical exercise in older adults (O'Brien et al., 2017). The training studies identified in the systematic review of Chapter 2 found physical exercise or movement-based programmes led to gains in multisensory processing performance, e.g., 12 week chiropractic care reduced SiFI susceptibility in community-dwelling older adults (Holt et al., 2016). Furthermore physical activity levels have been associated with multisensory integration precision, such that greater activity levels have been linked to more correct performance on a visual-somatosensory task (Mahoney et al., 2015). A recent review of multisensory balance exercise for individuals with balance disorders found physical exercise regimes targeting multisensory processing had greater improvement in balance compared to traditional physical activity (Zhang et al., 2021). The multisensory exercises involved stimulating at least two sensory systems during exercise (e.g., visual, somatosensory, vestibular). For example, an RCT study found 3 months of multisensory exercise training outperformed 3 months of strength training in terms of improvements for functional balance in older adults (Alfieri et al., 2010). Multisensory exercise resulted in a 11.85% reduction in time to complete a clinical balance measure (TUG), with strength training resulting in only 3% reduction (Alfieri et al., 2010), speaking to the importance of integrated training programmes. Another study found a balance exercise programme specifically targeting multisensory reweighting improved reweighting and balance in older fallers (Allison et al., 2018). The case is made that standard physical exercise works by targeting physical function for improvement, whereas multisensory exercises aim to improve balance by modulating plasticity of the central nervous system (Stein & Rowland, 2020; Tjernström et al., 2016). These studies tie in with the literature identified in the systematic review, but as measures of multisensory integration were not included in the study design of multisensory exercise programmes, we cannot assume multisensory exercises lead to benefits for multisensory integration. The research on multisensory exercise and its benefits for balance highlight an unanswered question in the literature. Could physical activity, particularly those that recruit multisensory integration processes improve multisensory integration as well as balance in individuals characterised by multisensory deficits (i.e., fall-prone older adults)? Would multisensory integration benefits and balance gains be correlated in successfully trained individuals? This was one of the aims of Study Two and represents a piece of work that would provide further insights for our field. If physical/balance exercise is a contender for improving multisensory integration, which a number of studies provide evidence to this end (Appiah-Kubi & Wright, 2019; Holt et al., 2016; O'Brien et al., 2017), should we be focusing our efforts on adapting existing balance exercise programmes for older fallers to include elements that would target multisensory integration mechanisms?

Related to this point, is the question of what the optimal training programme would look like. Both in terms of maximising multisensory benefits and promoting engagement for target groups who may benefit most from training, e.g., older fallers, individuals with MCI. The current thesis provides some contribution to this query. Firstly, a case must be made for qualitative investigations to supplement the growing experimental work aimed at training multisensory processing. Older adults are known to be a 'hard-to-reach' population, with specific sub-groups of interest to multisensory research recognised as even more difficult to recruit and retain in research, e.g., fall-prone older adults, older adults with cognitive deficits. Yet, very little research has explored these groups' experiences of research, with only a single recent study looking into frail older adults' experiences of research participation (Berge et al., 2020).

Study Three of this thesis presents the first qualitative exploration of older fallers' experience of being involved in a research experiment and a number of key insights relevant to the field of multisensory processing are made. Firstly, the social aspect of research participation emerged as key theme in the interview data, both in terms of a motivator for participation and as a factor identified by participants as enjoyable for them. Secondly, older fallers' gave their feedback on the experimental testing sessions they completed in Study Two, which involved EEG monitoring as well as completion of the computer-based SiFI task. Both findings have implications for how we go about developing training for multisensory integration. In relation to the social side of participation, this is an important consideration for future studies aiming to test and develop multisensory training programmes for older populations. Older fallers have identified the social interactions with the research team as important for their enjoyment of the research and 'a trip out of the house' or safe social interaction motivated many participants to consent to participation. This offers us important information on what older fallers look for when deciding to join a research study and it also points to our obligation as researchers to ensure older adults are comfortable and their expectations met around research participation. Devising research procedures and timelines to ensure social interaction is facilitated between participant and researcher/research assistant may offer a means to address not only ethical obligations in terms of participant expectation and benefit but also may maximise recruitment and retention efforts in future falls research studies.

In a similar vein, another insight from the qualitative interviews pertained to the fallers' conceptualisation of their falls. Older fallers spoke of their falls as something they considered inevitable or 'just one of these things' which may partially account for low uptake and high dropout rate amongst falls prevention and intervention approaches (see McPhate et al., 2013; Nyman & Victor, 2012). Exercise classes for falls prevention are known to be hindered by high drop out rates and low uptake (as little as 10%; Day et al., 2002; Fabacher et al., 1994) amongst community-dwelling older adults. The finding that older fallers view their condition as something to be accepted is an important consideration for future interventions designed to target multisensory integration or any other novel aspect of falls-risk. While not central to our research topic, it is nevertheless a noteworthy finding in the thesis considering the dearth of qualitative work with fall-prone older adults. This conceptualisation of falls as something where 'nothing can be done' is important in light of the Health Belief model, whereby perceived efficacy of an intervention affects engagement and compliance with the intervention (Janz & Becker, 1984). In the broader aim of falls prevention and intervention, there may be need for research to uncover ways to promote engagement with services and programmes in individuals who may consider their condition untreatable.

Limitations

The limitations specific to each study are documented in the discussion sections of the corresponding Chapter, however a note on the overall limits of the current thesis is informative here. The impact of the Covid-19 pandemic on the presented thesis is evident, particularly in relation to Chapter 4 (Study Two), given that data collection involving EEG with older adults was interrupted, leading this work to be presented as pilot data and a study protocol as opposed to a finished study. Nevertheless, the pilot work for Study Two provides insights important for future research with similar research questions and in effect represents a first step in the exploration of the impact of public healthcare falls interventions on multisensory processing of fall-prone older adults. In addition, the Covid-19 pandemic brought with it unique opportunities for research and lead to the inclusion of an important element of this thesis; the more human aspect of older fallers' experiences of participating in research. The opportunity to work remotely with fall-prone participants who had partially completed Study Two lead to insights and feedback into their experience of research, an overlooked area in the literature. The constrains of conducting research during a pandemic also impacted Study Three, the qualitative piece carried out during the pandemic lockdown. This limited the study in two ways; telephone interviews were conducted due to social distancing requirements and there was a considerable time lapse between experimental participation and the follow-up interviews. Both of these methodology considerations must be noted.

A second limitation pertains to the collected neurophysiological data. Both Study Two and Three highlighted the challenges associated with conducting EEG research with older fallers, with Study Two limited by high numbers of artifacts in the data and Study Three outlining in participants' own words the challenges they faced in participating in the EEG aspect of the study. Despite the interruption to data collection due to Covid-19, data collection was completed for many older fallers. However, several participants' neurophysiological data could not be used due to artifacts. In light of the considerable participant burden on older fallers who engage with EEG testing, as well as the time cost of testing, using a simpler EEG system may have yielded more usable data. The signal to noise ratio represents a major methodological challenge in using EEG (Rowan & Tolunsky, 2003) and efforts are ongoing in finding optimal means to minimise noise and sources of interference. A growing number of studies are exploring the neural mechanisms of multisensory integration and the TBW, with early evidence suggesting a role for alpha peak frequency as a neural mechanism (London et al., 2022; Venskus & Hughes, 2021).

To the best of our knowledge, only one study has used EEG with older fallers, in order to monitor electrical brain activity during multisensory integration (Scurry et al., 2021). An important line of future research is the neural underpinnings of training effects on multisensory processing in fallers, and considering the methodological difficulties we encountered in this respect, the careful planning and need for further pilot work and patients' involvement in the design is evident. The trainability of multisensory perception is an exciting prospect, but an understanding of the brain mechanisms behind such effects is necessary in order to promote and validate the use of such interventions in healthcare settings.

Despite the aforementioned limitations, the work outlined in this thesis presents important insights and contributions to the field of multisensory research, advancing our knowledge on its trainability, link to ageing and falls, challenges associated with carrying out this research topic and experiences of older fallers in research. Ultimately, the work contributes to the knowledge base around multisensory processing, which is increasingly recognised as an important factor in healthy ageing. It is timely, aligning with the UN Decade of Healthy Ageing (World Health Organisation, 2020) and contributing to the research base on multisensory processing, which may represent a novel avenue for intervention and prevention strategies to support our older citizens' cognitive and functional abilities as they age.

Future Directions

There is much groundwork to be done before multisensory research translates into real world outcomes. However, the first steps towards this have been made, with recent work exploring the diagnostic potential of tests of multisensory integration for risk of falls and Alzheimer's disease. It appears we are closer to fulfilling the diagnostic utility of multisensory research than the intervention possibilities. This may be due to the obstacles we face in such an endeavour. Lessons from the cognitive training literature point to the intricacies of training benefits beyond the controlled laboratory environments where trainings are devised and developed. Given the general lack of far transfer observed for cognitive training, this is something to be considered for perceptual training also. It highlights the need for future training studies targeting multisensory integration to include measures to test far transfer. Namely, measures of clinical outcomes or functional ability. In the case of falls, this would constitute assessment of falls-risk, balance ability and postural control. For older adults more broadly, measures of ADLs, global cognition and mobility may be appropriate far transfer variables of interest. Few cognitive trainings have been efficacious in real world contexts, with studies ongoing to uncover why this is the case. Maintenance of training benefits is something which needs to be the focus of future research. Only one of the training studies identified by this thesis included a long-term follow-up of multisensory integration benefits post-training. This study (Virsu et al., 2008) which involved 8 weeks of multi-modal Simultaneity Judgement training, reported significant reductions in training gains over 7 months post-training, speaking to the need to identify the longevity of training gains across time. Longitudinal studies would provide much needed data on the maintenance of training gains and transfer following training cessation. In sum, future directions for research should include translational research jointly with efforts to delineate the processes underlying older adults' performance, where the application of multisensory integration training is at the forefront of our research endeavours. Specifically, the inclusion of clinical outcome measures as well as far transfer measures is needed in future training studies. Additionally, experimental work is required to identify valid contenders for training paradigms likely to induce lasting multisensory processing benefits for populations characterised by impairments in this perceptual function. From there, larger scale studies will be needed, including longitudinal designs in order to capture the true applied potential of training. Considering the link between multisensory processing, balance and falls, a parallel strand of research is needed to address ongoing issues with recruitment of fallers for both research and rehabilitation efforts. Collaborating with fallers during the process of designing novel falls interventions could prove effective, given the observed difficulties and barriers to their contribution and participation in the research world.

Conclusion

There is much cause to be excited and encouraged by the growth of multisensory research, particularly in relation its association with ageing and in the context of an ageing global demographic. Multisensory processing is a blossoming area of research and one that represents much promise in terms of applied value for ageing. In an ideal world, the end goal of all research is to adapt and evolve the world we live in, and we as researchers are tasked with ensuring research realises its societal and real-world impact. This thesis presents evidence for the trainability of multisensory integration, while also highlighting the gaps in our knowledge that need addressing before intervention prospects can be seen. These include further knowledge into training mechanisms, the optimal training type to induce multisensory benefits and generalisability of training. We then focus on falls, an aspect of ageing where multisensory research holds promise for novel rehabilitation and prevention avenues. Key insights from experimental work and interviews with older faller participants offer valuable knowledge for future efforts aiming to bring this research field one step closer to realising its real world impact.

References

Alais, D., & Cass, J. (2010). Multisensory perceptual learning of temporal order: Audiovisual learning transfers to vision but not audition. *PloS One*, *5*(6), e11283.

Alais, D., Newell, F., & Mamassian, P. (2010). Multisensory processing in review: From physiology to behaviour. *Seeing and Perceiving*, *23*(1), 3–38.

Alfieri, F. M., Riberto, M., Gatz, L. S., Ribeiro, C. P. C., Lopes, J. A. F., Santarém, J. M., & Battistella, L. R. (2010). Functional mobility and balance in community-dwelling elderly submitted to multisensory versus strength exercises. *Clinical Interventions in Aging*, *5*, 181.

Allison, L. K., Kiemel, T., & Jeka, J. J. (2018). Sensory-challenge balance exercises improve multisensory reweighting in fall-prone older adults. *Journal of Neurologic Physical Therapy*, *42*(2), 84–93.

Appiah-Kubi, K. O., & Wright, W. G. (2019). Vestibular training promotes adaptation of multisensory integration in postural control. *Gait & Posture*, *73*, 215–220.

Babiloni, C., Barry, R. J., Başar, E., Blinowska, K. J., Cichocki, A., Drinkenburg, W. H., Klimesch, W., Knight, R. T., da Silva, F. L., & Nunez, P. (2020). International Federation of Clinical Neurophysiology (IFCN)–EEG research workgroup: Recommendations on frequency and topographic analysis of resting state EEG rhythms. Part 1: Applications in clinical research studies. *Clinical Neurophysiology*, *131*(1), 285–307.

Baczynska, A. M., Shaw, S. C., Patel, H. P., Sayer, A. A., & Roberts, H. C. (2017). Learning from older peoples' reasons for participating in demanding, intensive epidemiological studies: A qualitative study. *BMC Medical Research Methodology*, *17*(1), 1–9.

Barnett-Cowan, M. (2018). Introduction to the special issue on multisensory processing and aging. *Multisensory Research*, *31*(3–4), 145–149.

Barrett, A., Savva, G., Timonen, V., & Kenny, R. A. (2011). Fifty plus in Ireland 2011: First results from the Irish Longitudinal Study on Ageing (TILDA). *Dublin: Trinity College Dublin*.

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

Beauchamp, M. S., Lee, K. E., Argall, B. D., & Martin, A. (2004). Integration of auditory and visual information about objects in superior temporal sulcus. *Neuron*, *41*(5), 809–823.

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

Berg, K. O. (1992). Measuring balance in the Elderly: Validation of an Instruments. *Can J Public Health*, *83*, S7–S11.

Berge, I., Barenfeld, E., Dahlin-Ivanoff, S., Haak, M., & Lood, Q. (2020). Challenging oneself on the threshold to the world of research–frail older people's experiences of involvement in research. *BMC Geriatrics*, *20*(1), 1–10.

Bhangu, J., McMahon, C. G., Hall, P., Bennett, K., Rice, C., Crean, P., Sutton, R., & Kenny, R.-A. (2016). Long-term cardiac monitoring in older adults with unexplained falls and syncope. *Heart*, *102*(9), 681–686.

Bourgeois, F. T., Olson, K. L., Tse, T., Ioannidis, J. P., & Mandl, K. D. (2016). Prevalence and characteristics of interventional trials conducted exclusively in elderly persons: A cross-sectional analysis of registered clinical trials. *PloS One*, *11*(5), e0155948.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101.

Bronstein, A. M. (2016). Multisensory integration in balance control. *Handbook of Clinical Neurology*, *137*, 57–66.

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.

Cabeza, R., Albert, M., Belleville, S., Craik, F. I., Duarte, A., Grady, C. L., Lindenberger, U., Nyberg, L., Park, D. C., & Reuter-Lorenz, P. A. (2018). Maintenance, reserve and compensation: The cognitive neuroscience of healthy ageing. *Nature Reviews Neuroscience*, *19*(11), 701–710.

Cappe, C., Rouiller, E. M., & Barone, P. (2012). *Cortical and thalamic pathways for multisensory and sensorimotor interplay*.

Cecere, R., Gross, J., & Thut, G. (2016). Behavioural evidence for separate mechanisms of audiovisual temporal binding as a function of leading sensory modality. *European Journal of Neuroscience*, *43*(12), 1561–1568.

Chan, J. S., Connolly, S. K., & Setti, A. (2018). The number of stimulus-onset asynchronies affects the perception of the sound-induced flash illusion in young and older adults. *Multisensory Research*, *31*(3–4), 175–190.

Chan, J. S., Wibral, M., Stawowsky, C., Brandl, M., Helbling, S., Naumer, M. J., Kaiser, J., & Wollstadt, P. (2021). Predictive coding over the lifespan: Increased reliance on perceptual priors in older adults—A magnetoencephalography and dynamic causal modeling study. *Frontiers in Aging Neuroscience*, *13*.

Chang, Y.-K., Labban, J. D., Gapin, J. I., & Etnier, J. L. (2012). The effects of acute exercise on cognitive performance: A meta-analysis. *Brain Research*, *1453*, 87–101.

Chiba, R., Takakusaki, K., Ota, J., Yozu, A., & Haga, N. (2016). Human upright posture control models based on multisensory inputs; in fast and slow dynamics. *Neuroscience Research*, *104*, 96–104.

Clark, J. G. (1981). Uses and abuses of hearing loss classification. *Asha*, *23*(7), 493–500.

Colonius, H., & Diederich, A. (2004). Multisensory interaction in saccadic reaction time: A time-window-of-integration model. *Journal of Cognitive Neuroscience*, *16*(6), 1000–1009.

Colonius, H., & Diederich, A. (2020). Formal models and quantitative measures of multisensory integration: A selective overview. *European Journal of Neuroscience*, *51*(5), 1161–1178.

Cornelio, P., Velasco, C., & Obrist, M. (2021). Multisensory integration as per technological advances: A review. *Frontiers in Neuroscience*, 614.

Craig, C. L., Marshall, A. L., Sjöström, M., Bauman, A. E., Booth, M. L., Ainsworth, B. E., Pratt, M., Ekelund, U. L. F., Yngve, A., & Sallis, J. F. (2003). International physical activity questionnaire: 12-country reliability and validity. *Medicine & Science in Sports & Exercise*, *35*(8), 1381–1395.

Craig, C., Marshall, A., Sjostrom, M., Bauman, A., Lee, P., Macfarlane, D., Lam, T., & Stewart, S. (2017). International physical activity questionnaire-short form. *J Am Coll Health*, *65*(7), 492–501.

Creswell, J. W., & Creswell, J. (2003). *Research design*. Sage publications Thousand Oaks, CA.

CSO. (2019). *CSO statistical release: Population and migration estimates*. Central Statistics Office Cork.

Davies, A. J., & Kenny, R. A. (1996). Falls presenting to the accident and emergency department: Types of presentation and risk factor profile. *Age and Ageing*, *25*(5), 362–366.

Davis, J. C., Robertson, M. C., Ashe, M. C., Liu-Ambrose, T., Khan, K. M., & Marra, C. A. (2010). Does a home-based strength and balance programme in people aged≥ 80 years provide the best value for money to prevent falls? A systematic review of economic evaluations of falls prevention interventions. *British Journal of Sports Medicine*, *44*(2), 80–89.

Day, L., Fildes, B., Gordon, I., Fitzharris, M., Flamer, H., & Lord, S. (2002). Randomised factorial trial of falls prevention among older people living in their own homes. *Bmj*, *325*(7356), 128.

de Boer-Schellekens, L., & Vroomen, J. (2014). Multisensory integration compensates loss of sensitivity of visual temporal order in the elderly. *Experimental Brain Research*, *232*(1), 253–262.

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*, 80.

De Niear, M. A., Gupta, P. B., Baum, S. H., & Wallace, M. T. (2018). Perceptual training enhances temporal acuity for multisensory speech. *Neurobiology of Learning and Memory*, *147*, 9–17.

De Niear, M. A., Koo, B., & Wallace, M. T. (2016). Multisensory perceptual learning is dependent upon task difficulty. *Experimental Brain Research*, *234*(11), 3269–3277.

De Niear, M. A., Noel, J.-P., & Wallace, M. T. (2017). The impact of feedback on the different time courses of multisensory temporal recalibration. *Neural Plasticity*, *2017*.

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.

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.

DeLoss, D. J., Watanabe, T., & Andersen, G. J. (2015). Improving vision among older adults: Behavioral training to improve sight. *Psychological Science*, *26*(4), 456–466.

Diaconescu, A. O., Hasher, L., & McIntosh, A. R. (2013). Visual dominance and multisensory integration changes with age. *Neuroimage*, *65*, 152–166.

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

Donoghue, O. A., Hernandez, B., O'Connell, M. D., & Kenny, R. A. (2022). Using conditional inference forests to examine predictive ability for future falls and syncope in older adults: Results from The Irish Longitudinal Study on Ageing. *The Journals of Gerontology: Series A*.

Elliott, M. T., Wing, A. M., & Welchman, A. E. (2011). The effect of ageing on multisensory integration for the control of movement timing. *Experimental Brain Research*, *213*(2), 291–298.

Fabacher, D., Josephson, K., Pietruszka, F., Linderborn, K., Morley, J. E., & Rubenstein, L. Z. (1994). An in-home preventive assessment program for independent older adults: A randomized controlled trial. *Journal of the American Geriatrics Society*, *42*(6), 630–638.

Ferrucci, L., Guralnik, J. M., Studenski, S., Fried, L. P., Cutler Jr, G. B., Walston, J. D., & Group, I. on F. W. (2004). Designing randomized, controlled trials aimed at preventing or delaying functional decline and disability in frail, older persons: A consensus report. *Journal of the American Geriatrics Society*, *52*(4), 625–634.

Festa, E. K., Katz, A. P., Ott, B. R., Tremont, G., & Heindel, W. C. (2017). Dissociable effects of aging and mild cognitive impairment on bottom-up audiovisual integration. *Journal of Alzheimer's Disease*, *59*(1), 155–167.

Festa, E., Katz, A., Ott, B., & Heindel, W. (2013). P2–256: Perceptual binding of audiovisual speech information is disrupted at the preclinical stage of Alzheimer's disease. *Alzheimer's & Dementia*, *9*, P452–P452.

Folstein, M., Folstein, S., & McHugh, P. (1975). Mini-mental state (mmse) journal of psychiatric research, 12. *J. Psychiatr. Res*.

Freiherr, J., Lundström, J. N., Habel, U., & Reetz, K. (2013). Multisensory integration mechanisms during aging. *Frontiers in Human Neuroscience*, *7*, 863.

Gannon, B., O'Shea, E., & Hudson, E. (2007). The economic costs of falls and fractures in people aged 65 and over in Ireland. *Irish Centre for Social Gerontology, Galway*.

Gardiner, S., Glogowska, M., Stoddart, C., Pendlebury, S., Lasserson, D., & Jackson, D. (2017). Older people's experiences of falling and perceived risk of falls in the community: A narrative synthesis of qualitative research. *International Journal of Older People Nursing*, *12*(4), e12151.

Ghazanfar, A. A., & Schroeder, C. E. (2006). Is neocortex essentially multisensory? *Trends in Cognitive Sciences*, *10*(6), 278–285.

Giacino, J. T., Fins, J. J., Laureys, S., & Schiff, N. D. (2014). Disorders of consciousness after acquired brain injury: The state of the science. *Nature Reviews Neurology*, *10*(2), 99–114.

Goldstone, R. L. (1998). Perceptual learning. *Annual Review of Psychology*, *49*(1), 585–612.

Gomez-Pinilla, F., & Hillman, C. (2013). The influence of exercise on cognitive abilities. *Comprehensive Physiology*, *3*(1), 403.

Green, C. S., Banai, K., Lu, Z.-L., & Bavelier, D. (2018). Perceptual learning. *Stevens' Handbook of Experimental Psychology and Cognitive Neuroscience*, *2*, 1–47.

Green, C. S., & Bavelier, D. (2008). Exercising your brain: A review of human brain plasticity and training-induced learning. *Psychology and Aging*, *23*(4), 692.

Haagsma, J. A., Graetz, N., Bolliger, I., Naghavi, M., Higashi, H., Mullany, E. C., Abera, S. F., Abraham, J. P., Adofo, K., & Alsharif, U. (2016). The global burden of injury: Incidence, mortality, disability-adjusted life years and time trends from the Global Burden of Disease study 2013. *Injury Prevention*, *22*(1), 3–18.

Hairston, W. D., Laurienti, P. J., Mishra, G., Burdette, J. H., & Wallace, M. T. (2003). Multisensory enhancement of localization under conditions of induced myopia. *Experimental Brain Research*, *152*(3), 404–408.

Harrar, V., Tammam, J., Pérez-Bellido, A., Pitt, A., Stein, J., & Spence, C. (2014). Multisensory integration and attention in developmental dyslexia. *Current Biology*, *24*(5), 531–535.

Hauer, K., Yardley, L., Beyer, N., Kempen, G., Dias, N., Campbell, M., Becker, C., & Todd, C. (2010). Validation of the Falls Efficacy Scale and Falls Efficacy Scale International in geriatric patients with and without cognitive impairment: Results of self-report and interview-based questionnaires. *Gerontology*, *56*(2), 190–199.

Health, N. I. for, & Excellence, C. (2013). *Falls in older people: Assessing risk and prevention*. NICE.

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.

Higgins, J. P., Altman, D. G., Gøtzsche, P. C., Jüni, P., Moher, D., Oxman, A. D., Savović, J., Schulz, K. F., Weeks, L., & Sterne, J. A. (2011). The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. *Bmj*, *343*.

Hillock-Dunn, A., & Wallace, M. T. (2012). Developmental changes in the multisensory temporal binding window persist into adolescence. *Developmental Science*, *15*(5), 688–696.

Hipp, J. F., & Siegel, M. (2013). Dissociating neuronal gamma-band activity from cranial and ocular muscle activity in EEG. *Frontiers in Human Neuroscience*, *7*, 338.

Hirst, R. J., McGovern, D. P., Setti, A., Shams, L., & Newell, F. N. (2020). What you see is what you hear: Twenty years of research using the Sound-Induced Flash Illusion. *Neuroscience & Biobehavioral Reviews*.

Hirst, R. J., Setti, A., De Looze, C., Kenny, R. A., & Newell, F. N. (2022). Multisensory integration precision is associated with better cognitive performance over time in older adults: A large-scale exploratory study. *Aging Brain*, *2*, 100038.

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), 1–12.

Hirst, R. J., Whelan, R., Boyle, R., Setti, A., Knight, S., O'Connor, J., Williamson, W., McMorrow, J., Fagan, A. J., & Meaney, J. F. (2021). Gray matter volume in the right angular gyrus is associated with differential patterns of multisensory integration with aging. *Neurobiology of Aging*, *100*, 83–90.

Holt, K. R., Haavik, H., Lee, A. C. L., Murphy, B., & Elley, C. R. (2016). Effectiveness of chiropractic care to improve sensorimotor function associated with falls risk in older people: A randomized controlled trial. *Journal of Manipulative and Physiological Therapeutics*, *39*(4), 267–278.

Hopewell, S., Adedire, O., Copsey, B. J., Boniface, G. J., Sherrington, C., Clemson, L., Close, J. C., & Lamb, S. E. (2018). Multifactorial and multiple component interventions for preventing falls in older people living in the community. *Cochrane Database of Systematic Reviews*, *7*.

Horsfall, R. P., Wuerger, S. M., & Meyer, G. F. (2021). Narrowing of the Audiovisual Temporal Binding Window Due To Perceptual Training Is Specific to High Visual Intensity Stimuli. *I-Perception*, *12*(1), 2041669520978670.

Huang, J., Wang, E., Lu, K., Wang, A., & Zhang, M. (2022). Long-term training reduces the responses to the sound-induced flash illusion. *Attention, Perception, & Psychophysics*, *84*(2), 529–539.

Janz, N. K., & Becker, M. H. (1984). The health belief model: A decade later. *Health Education Quarterly*, *11*(1), 1–47.

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

Kaiser, M., Senkowski, D., Busch, N. A., Balz, J., & Keil, J. (2019). Single trial prestimulus oscillations predict perception of the sound-induced flash illusion. *Scientific Reports*, *9*(1), 1–8.

Kannus, P., Parkkari, J., Koskinen, S., Niemi, S., Palvanen, M., Järvinen, M., & Vuori, I. (1999). Fall-induced injuries and deaths among older adults. *Jama*, *281*(20), 1895–1899.

Keil, J., Müller, N., Hartmann, T., & Weisz, N. (2014). Prestimulus beta power and phase synchrony influence the sound-induced flash illusion. *Cerebral Cortex*, *24*(5), 1278–1288.

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

Klug, M., & Gramann, K. (2021). Identifying key factors for improving ICA-based decomposition of EEG data in mobile and stationary experiments. *European Journal of Neuroscience*, *54*(12), 8406–8420.

Koen, J. D., & Rugg, M. D. (2019). Neural dedifferentiation in the aging brain. *Trends in Cognitive Sciences*, *23*(7), 547–559.

Kramer, A., Röder, B., & Bruns, P. (2020). Feedback modulates audio-visual spatial recalibration. *Frontiers in Integrative Neuroscience*, *13*, 74.

Laffoy, M. (2008). *Strategy to prevent falls and fractures in Ireland's ageing population summary, conclusions and recomendations*.

Lam, F. M., Huang, M.-Z., Liao, L.-R., Chung, R. C., Kwok, T. C., & Pang, M. Y. (2018). Physical exercise improves strength, balance, mobility, and endurance in people with cognitive impairment and dementia: A systematic review. *Journal of Physiotherapy*, *64*(1), 4–15.

Lambourne, K., & Tomporowski, P. (2010). The effect of exercise-induced arousal on cognitive task performance: A meta-regression analysis. *Brain Research*, *1341*, 12–24.

Lange, J., Oostenveld, R., & Fries, P. (2013). Reduced occipital alpha power indexes enhanced excitability rather than improved visual perception. *Journal of Neuroscience*, *33*(7), 3212–3220.

Larsen, R. T., Korfitsen, C. B., Keller, C., Christensen, J., Andersen, H. B., Juhl, C., & Langberg, H. (2021). The MIPAM trial–motivational interviewing and physical activity monitoring to enhance the daily level of physical activity among older adults–a randomized controlled trial. *European Review of Aging and Physical Activity*, *18*(1), 1–15.

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.

Lavedán, A., Viladrosa, M., Jürschik, P., Botigué, T., Nuín, C., Masot, O., & Lavedán, R. (2018). Fear of falling in community-dwelling older adults: A cause of falls, a consequence, or both? *PLoS One*, *13*(3), e0194967.

Lewald, J., Falkenstein, M., & Schwarz, M. (2006). Abnormal auditory-visual crossmodal temporal-order judgments in Parkinson's disease. *Cognitive Processing*, *7*(1), 134–134.

London, R. E., Benwell, C. S., Cecere, R., Quak, M., Thut, G., & Talsma, D. (2022). EEG Alpha power predicts the temporal sensitivity of multisensory perception. *European Journal of Neuroscience*.

Lupo, J., & Barnett-Cowan, M. (2017). Perceived timing of a postural perturbation. *Neuroscience Letters*, *639*, 167–172.

Lupo, J., & Barnett-Cowan, M. (2018). Impaired perceived timing of falls in the elderly. *Gait & Posture*, *59*, 40–45.

Ma, L.-L., Wang, Y.-Y., Yang, Z.-H., Huang, D., Weng, H., & Zeng, X.-T. (2020). Methodological quality (risk of bias) assessment tools for primary and secondary medical studies: What are they and which is better? *Military Medical Research*, *7*(1), 1–11.

Macaluso, E. (2006). Multisensory processing in sensory-specific cortical areas. *The Neuroscientist*, *12*(4), 327–338.

Maccarthy, J., Guerin, S., Wilson, A. G., & Dorris, E. R. (2019). Facilitating public and patient involvement in basic and preclinical health research. *PLoS One*, *14*(5), e0216600.

Mahoney, J. R., & Barnett-Cowan, M. (2019). Introduction to the special issue on multisensory processing and aging (Part II): Links to clinically meaningful outcomes. *Multisensory Research*, *32*(8), 665–670.

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.

Mahoney, J. R., Dumas, K., & Holtzer, R. (2015). Visual–somatosensory integration is linked to physical activity level in older adults. *Multisensory Research*, *28*(1–2), 11–29.

Mahoney, J. R., George, C. J., & Verghese, J. (2022). Introducing CatchUTM: A Novel Multisensory Tool for Assessing Patients' Risk of Falling. *Journal of Perceptual Imaging*, *5*, 1–6.

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., & Verghese, J. (2018). Visual-somatosensory integration and quantitative gait performance in aging. *Frontiers in Aging Neuroscience*, *10*, 377.

Mahoney, J. R., Verghese, J., Dumas, K., Wang, C., & Holtzer, R. (2012). The effect of multisensory cues on attention in aging. *Brain Research*, *1472*, 63–73.

Maniglia, M., & Seitz, A. R. (2018). Towards a whole brain model of Perceptual Learning. *Current Opinion in Behavioral Sciences*, *20*, 47–55.

Marcantonio, E. R., Aneja, J., Jones, R. N., Alsop, D. C., Fong, T. G., Crosby, G. J., Culley, D. J., Cupples, L. A., & Inouye, S. K. (2008). Maximizing clinical research participation in vulnerable older persons: Identification of barriers and motivators. *Journal of the American Geriatrics Society*, *56*(8), 1522–1527.

McGovern, D. P., Astle, A. T., Clavin, S. L., & Newell, F. N. (2016). Task-specific transfer of perceptual learning across sensory modalities. *Current Biology*, *26*(1), R20–R21.

McGovern, D. P., Burns, S., Hirst, R. J., & Newell, F. N. (2022). Perceptual training narrows the temporal binding window of audiovisual integration in both younger and older adults. *Neuropsychologia*, *173*, 108309.

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.

McPhate, L., Simek, E. M., & Haines, T. P. (2013). Program-related factors are associated with adherence to group exercise interventions for the prevention of falls: A systematic review. *Journal of Physiotherapy*, *59*(2), 81–92.

Melby-Lervåg, M., Redick, T. S., & Hulme, C. (2016). Working memory training does not improve performance on measures of intelligence or other measures of “far transfer” evidence from a meta-analytic review. *Perspectives on Psychological Science*, *11*(4), 512–534.

Meredith, M. A., & Stein, B. E. (1986). Visual, auditory, and somatosensory convergence on cells in superior colliculus results in multisensory integration. *Journal of Neurophysiology*, *56*(3), 640–662.

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.

Meyer, G. F., & Noppeney, U. (2011). Multisensory integration: From fundamental principles to translational research. In *Experimental brain research* (Vol. 213, Issue 2, pp. 163–166). Springer.

Miller, G. A. (1969). Psychology as a means of promoting human welfare. *American Psychologist*, *24*(12), 1063.

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.

Mody, L., Miller, D. K., McGloin, J. M., Freeman, M., Marcantonio, E. R., Magaziner, J., & Studenski, S. (2008). Recruitment and Retention of Older Adults in Aging Research: (See editorial comments by Dr. Stephanie Studenski, pp 2351–2352). *Journal of the American Geriatrics Society*, *56*(12), 2340–2348.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & Group*, P. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Annals of Internal Medicine*, *151*(4), 264–269.

Moore, D. S., & Ellis, R. (2008). Measurement of fall-related psychological constructs among independent-living older adults: A review of the research literature. *Aging and Mental Health*, *12*(6), 684–699.

Moreau, D., & Conway, A. R. (2014). The case for an ecological approach to cognitive training. *Trends in Cognitive Sciences*, *18*(7), 334–336.

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*.

Mozolic, J. L., Long, A. B., Morgan, A. R., Rawley-Payne, M., & Laurienti, P. J. (2011). A cognitive training intervention improves modality-specific attention in a randomized controlled trial of healthy older adults. *Neurobiology of Aging*, *32*(4), 655–668.

Murphy, E., Tierney, E., Shé, É. N., Killilea, M., Donaghey, C., Daly, A., Roche, M., Mac Loughlin, D., Ignite, P. P. I., & Panel, N. G. P. A. (2020). COVID-19: Public and patient involvement, now more than ever. *HRB Open Research*, *3*.

Murray, M. M., Eardley, A. F., Edginton, T., Oyekan, R., Smyth, E., & Matusz, P. J. (2018). Sensory dominance and multisensory integration as screening tools in aging. *Scientific Reports*, *8*(1), 1–11.

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.

Muthukumaraswamy, S. D. (2013). High-frequency brain activity and muscle artifacts in MEG/EEG: A review and recommendations. *Frontiers in Human Neuroscience*, *7*, 138.

National Institue for Health and Care Research. (2021). *Briefing notes for researchers—Public involvement in NHS, health and social care research*. NIHR. https://www.nihr.ac.uk/documents/briefing-notes-for-researchers-public-involvement-in-nhs-health-and-social-care-research/27371

Noel, J.-P., De Niear, M., Van der Burg, E., & Wallace, M. T. (2016). Audiovisual simultaneity judgment and rapid recalibration throughout the lifespan. *PloS One*, *11*(8), e0161698.

Nolan, A., Ma, Y., & Moore, P. (2016). Changes in public healthcare entitlement and healthcare utilisation among the older population in Ireland. *Dublin: The Irish Longitudinal Study on Ageing*.

Nyman, S. R., & Victor, C. R. (2012). Older people's participation in and engagement with falls prevention interventions in community settings: An augment to the Cochrane systematic review. *Age and Ageing*, *41*(1), 16–23.

O'Brien, J. M., Chan, J. S., & Setti, A. (2020). Audio-visual training in older adults: 2-interval-forced choice task improves performance. *Frontiers in Neuroscience*, 1132.

O'Brien, J., Ottoboni, G., Tessari, A., & Setti, A. (2017). One bout of open skill exercise improves cross-modal perception and immediate memory in healthy older adults who habitually exercise. *PLoS One*, *12*(6), e0178739.

O'Brien, J., Ottoboni, G., Tessari, A., & Setti, A. (2021). Multisensory Perception, Verbal, Visuo-spatial and motor working memory modulation after a single open-or closed-skill exercise session in children. *Journal of Cognitive Enhancement*, *5*(2), 141–154.

Ocloo, J., & Matthews, R. (2016). From tokenism to empowerment: Progressing patient and public involvement in healthcare improvement. *BMJ Quality & Safety*, *25*(8), 626–632.

O'Dowd, A., Hirst, R. J., Setti, A., Donoghue, O. A., Kenny, R. A., & Newell, F. N. (2022). *The temporal precision of audio-visual integration is associated with ten-year fall number but not sensorimotor fall risk in older adults*.

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J.-M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*, *2011*.

Oostenveld, R., & Praamstra, P. (2001). The five percent electrode system for high-resolution EEG and ERP measurements. *Clinical Neurophysiology*, *112*(4), 713–719.

Pantev, C., Paraskevopoulos, E., Kuchenbuch, A., Lu, Y., & Herholz, S. C. (2015). Musical expertise is related to neuroplastic changes of multisensory nature within the auditory cortex. *European Journal of Neuroscience*, *41*(5), 709–717.

Paraskevoudi, N., Balcı, F., & Vatakis, A. (2018). “Walking” through the sensory, cognitive, and temporal degradations of healthy aging. *Annals of the New York Academy of Sciences*, *1426*(1), 72–92.

Parker, J. L., & Robinson, C. W. (2018). Changes in multisensory integration across the life span. *Psychology and Aging*, *33*(3), 545.

Pellicer, M. G., Lusar, A. C., Casanovas, J. M., & Ferrer, B.-C. S. (2017). Effectiveness of a multimodal exercise rehabilitation program on walking capacity and functionality after a stroke. *Journal of Exercise Rehabilitation*, *13*(6), 666.

Pesce, C. (2009). *An integrated approach to the effect of acute and chronic exercise on cognition: The linked role of individual and task constraints.*

Pinto, J. O., Dores, A. R., Peixoto, B., Vieira de Melo, B. B., & Barbosa, F. (2022). Critical review of Multisensory Integration programs and proposal of a theoretical framework for its combination with neurocognitive training. *Expert Review of Neurotherapeutics*, 1–10.

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*(2), 142–148.

Powers, A. R., Hillock, A. R., & Wallace, M. T. (2009). Perceptual training narrows the temporal window of multisensory binding. *Journal of Neuroscience*, *29*(39), 12265–12274.

Powers III, A. R., Hillock-Dunn, A., & Wallace, M. T. (2016). Generalization of multisensory perceptual learning. *Scientific Reports*, *6*(1), 1–9.

Prioli, A. C., Júnior, P. B. F., & Barela, J. A. (2005). Physical activity and postural control in the elderly: Coupling between visual information and body sway. *Gerontology*, *51*(3), 145–148.

Pu, L., Lion, K. M., Todorovic, M., & Moyle, W. (2021). Portable EEG monitoring for older adults with dementia and chronic pain-A feasibility study. *Geriatric Nursing*, *42*(1), 124–128.

Ratey, J. J., & Loehr, J. E. (2011). *The positive impact of physical activity on cognition during adulthood: A review of underlying mechanisms, evidence and recommendations*.

Rebok, G. W., Ball, K., Guey, L. T., Jones, R. N., Kim, H.-Y., King, J. W., Marsiske, M., Morris, J. N., Tennstedt, S. L., & Unverzagt, F. W. (2014). Ten-year effects of the advanced cognitive training for independent and vital elderly cognitive training trial on cognition and everyday functioning in older adults. *Journal of the American Geriatrics Society*, *62*(1), 16–24.

Ren, Y., Suzuki, K., Yang, W., Ren, Y., Wu, F., Yang, J., Takahashi, S., Ejima, Y., Wu, J., & Hirata, K. (2018). Absent audiovisual integration elicited by peripheral stimuli in Parkinson's disease. *Parkinson's Disease*, *2018*.

Rosenthal, O., Shimojo, S., & Shams, L. (2009). Sound-induced flash illusion is resistant to feedback training. *Brain Topography*, *21*(3), 185–192.

Rossini, P. M., Rossi, S., Babiloni, C., & Polich, J. (2007). Clinical neurophysiology of aging brain: From normal aging to neurodegeneration. *Progress in Neurobiology*, *83*(6), 375–400.

Rowan, A. J., & Tolunsky, E. (2003). *A primer of EEG: With a mini-atlas*. Elsevier España.

Rowe, J. W., & Kahn, R. L. (1997). Successful aging. *The Gerontologist*, *37*(4), 433–440.

S Chan, J., Kaiser, J., Brandl, M., Matura, S., Prvulovic, D., J Hogan, M., & J Naumer, M. (2015). Expanded temporal binding windows in people with mild cognitive impairment. *Current Alzheimer Research*, *12*(1), 61–68.

Sala, G., Aksayli, N. D., Tatlidil, K. S., Tatsumi, T., Gondo, Y., & Gobet, F. (2019). Near and far transfer in cognitive training: A second-order meta-analysis. *Collabra: Psychology*, *5*(1).

Sala, G., & Gobet, F. (2019). Cognitive training does not enhance general cognition. *Trends in Cognitive Sciences*, *23*(1), 9–20.

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*(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.

Shams, L., Kamitani, Y., & Shimojo, S. (2002). Visual illusion induced by sound. *Cognitive Brain Research*, *14*(1), 147–152.

Shams, L., & Seitz, A. R. (2008). Benefits of multisensory learning. *Trends in Cognitive Sciences*, *12*(11), 411–417.

Sherrington, C., Fairhall, N., Kwok, W., Wallbank, G., Tiedemann, A., Michaleff, Z. A., Ng, C. A., & Bauman, A. (2020). Evidence on physical activity and falls prevention for people aged 65+ years: Systematic review to inform the WHO guidelines on physical activity and sedentary behaviour. *International Journal of Behavioral Nutrition and Physical Activity*, *17*(1), 1–9.

Sherrington, C., Fairhall, N., Wallbank, G., Tiedemann, A., Michaleff, Z. A., Howard, K., Clemson, L., Hopewell, S., & Lamb, S. (2020). Exercise for preventing falls in older people living in the community: An abridged Cochrane systematic review. *British Journal of Sports Medicine*, *54*(15), 885–891.

Shumway-Cook, A., & Woollacott, M. H. (2007). *Motor control: Translating research into clinical practice*. Lippincott Williams & Wilkins.

Slim, K., Nini, E., Forestier, D., Kwiatkowski, F., Panis, Y., & Chipponi, J. (2003). Methodological index for non-randomized studies (MINORS): Development and validation of a new instrument. *ANZ Journal of Surgery*, *73*(9), 712–716.

Stam, C. J., Montez, T., Jones, B. F., Rombouts, S., Van Der Made, Y., Pijnenburg, Y. A. L., & Scheltens, P. (2005). Disturbed fluctuations of resting state EEG synchronization in Alzheimer's disease. *Clinical Neurophysiology*, *116*(3), 708–715.

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*(2), 423–434.

Stein, B. E. (2012). *The new handbook of multisensory processing*. Mit Press.

Stein, B. E., & Meredith, M. A. (1990). Multisensory integration: Neural and behavioral solutions for dealing with stimuli from different sensory modalities. *Annals of the New York Academy of Sciences*.

Stein, B. E., & Rowland, B. A. (2020). Neural development of multisensory integration. In *Multisensory Perception* (pp. 57–87). Elsevier.

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.

Stevenson, R. A., Ghose, D., Fister, J. K., Sarko, D. K., Altieri, N. A., Nidiffer, A. R., Kurela, L. R., Siemann, J. K., James, T. W., & Wallace, M. T. (2014). Identifying and quantifying multisensory integration: A tutorial review. *Brain Topography*, *27*(6), 707–730.

Stevenson, R. A., Siemann, J. K., Woynaroski, T. G., Schneider, B. C., Eberly, H. E., Camarata, S. M., & Wallace, M. T. (2014). Evidence for diminished multisensory integration in autism spectrum disorders. *Journal of Autism and Developmental Disorders*, *44*(12), 3161–3167.

Stevenson, R. A., Wilson, M. M., Powers, A. R., & Wallace, M. T. (2013). The effects of visual training on multisensory temporal processing. *Experimental Brain Research*, *225*(4), 479–489.

Stojanoski, B., Lyons, K. M., Pearce, A. A., & Owen, A. M. (2018). Targeted training: Converging evidence against the transferable benefits of online brain training on cognitive function. *Neuropsychologia*, *117*, 541–550.

Sürig, R., Bottari, D., & Röder, B. (2018). Transfer of audio-visual temporal training to temporal and spatial audio-visual tasks. *Multisensory Research*, *31*(6), 556–578.

Theves, S., Chan, J. S., Naumer, M. J., & Kaiser, J. (2020). Improving audio-visual temporal perception through training enhances beta-band activity. *Neuroimage*, *206*, 116312.

Tinetti, M. E., Speechley, M., & Ginter, S. F. (1988). Risk factors for falls among elderly persons living in the community. *New England Journal of Medicine*, *319*(26), 1701–1707.

Tinetti, M. E., & Williams, C. S. (1997). Falls, injuries due to falls, and the risk of admission to a nursing home. *New England Journal of Medicine*, *337*(18), 1279–1284.

Tjernström, F., Zur, O., & Jahn, K. (2016). Current concepts and future approaches to vestibular rehabilitation. *Journal of Neurology*, *263*(1), 65–70.

Todd, C., & Skelton, D. (2004). *What are the Main risk Factors for falls Amongst older people and what are the most Effective interventions to Prevent these falls?.* World Health Organization Copenhagen.

Troya, M. I., Chew-Graham, C. A., Babatunde, O., Bartlam, B., Higginbottom, A., & Dikomitis, L. (2019). Patient and public involvement and engagement in a doctoral research project exploring self-harm in older adults. *Health Expectations*, *22*(4), 617–631.

UNDESA. (2015). *World population ageing 2015*. http://www.un.org/en/development/desa/population/theme/ageing/WPA2015

Van der Burg, E., Alais, D., & Cass, J. (2013). Rapid recalibration to audiovisual asynchrony. *Journal of Neuroscience*, *33*(37), 14633–14637.

Venskus, A., & Hughes, G. (2021). Individual differences in alpha frequency are associated with the time window of multisensory integration, but not time perception. *Neuropsychologia*, *159*, 107919.

Virsu, V., Lahti-Nuuttila, P., & Laasonen, M. (2003). Crossmodal temporal processing acuity impairment aggravates with age in developmental dyslexia. *Neuroscience Letters*, *336*(3), 151–154.

Virsu, V., Oksanen-Hennah, H., Vedenpää, A., Jaatinen, P., & Lahti-Nuuttila, P. (2008). Simultaneity learning in vision, audition, tactile sense and their cross-modal combinations. *Experimental Brain Research*, *186*(4), 525–537.

Voermans, N. C., Snijders, A. H., Schoon, Y., & Bloem, B. R. (2007). Why old people fall (and how to stop them). *Practical Neurology*, *7*(3), 158–171.

Wahl, H.-W., Deeg, D., & Litwin, H. (2016). Successful ageing as a persistent priority in ageing research. In *European Journal of Ageing* (Vol. 13, Issue 1, pp. 1–3). Springer.

Wallace, M. T., Woynaroski, T. G., & Stevenson, R. A. (2020). Multisensory integration as a window into orderly and disrupted cognition and communication. *Annual Review of Psychology*, *71*, 193–219.

Williams, L. E. (2009). *Reduced multisensory integration in individuals with schizophrenia: Evidence from psychophysical studies*. University of California, San Diego.

World Health Organisation. (2020). *UN Decade of Healthy Ageing: Plan of action*. https://www.who.int/initiatives/decade-of-healthy-ageing

Yang, W., Guo, A., Li, Y., Qiu, J., Li, S., Yin, S., Chen, J., & Ren, Y. (2018). Audio-visual spatiotemporal perceptual training enhances the P300 component in healthy older adults. *Frontiers in Psychology*, 2537.

Zerr, M., Freihorst, C., Schütz, H., Sinke, C., Müller, A., Bleich, S., Münte, T. F., & Szycik, G. R. (2019). Brief sensory training narrows the temporal binding window and enhances long-term multimodal speech perception. *Frontiers in Psychology*, 2489.

Zhang, S., Liu, D., Yu, D., Zhu, Y., Xu, W.-C., Tian, E., Guo, Z.-Q., Shi, H., Yin, S., & Kong, W.-J. (2021). Multisensory exercise improves balance in people with balance disorders: A systematic review. *Current Medical Science*, *41*(4), 635–648.

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*.

Zhou, H., Cheung, E. F., & Chan, R. C. (2020). Audiovisual temporal integration: Cognitive processing, neural mechanisms, developmental trajectory and potential interventions. *Neuropsychologia*, *140*, 107396.

Appendix A: Older women's experiences of a community-led walking programme using activity trackers

(Full article can be accessed at: https://doi.org/10.3390/ijerph18189818)

Abstract

Promoting physical activity amongst older adults represents a major public health goal and community-led exercise programmes present benefits in promoting active lifestyles. Commercial activity trackers potentially encourage positive behaviour change with respect to physical exercise. This qualitative study investigated the experiences and attitudes of older adults following a 6- week community-led walking programme utilising activity trackers. Eleven community-dwelling older women aged 60+ completed individual phone interviews following their involvement in the programme. The programme, codesigned with a group of senior citizens, equipped participants with wrist-worn activity trackers and included biweekly check-in sessions with a researcher to monitor progress and support motivation. Interviews explored participants' experiences of the programme and of using activity trackers for the purpose of becoming more active. A thematic analysis produced three main themes: 'programme as a source of motivation', 'user experiences with the technology' and 'views on social dimension of the programme'. Overall, participants highlighted the self-monitoring function of activity trackers as most beneficial for their exercise levels. This study provides insights into the personal and social factors perceived by older adults in relation to being part of a community-led programme using activity trackers. It highlights the role of the programme and trackers in maintaining motivation to stay active.

Outputs

Published as O'Brien, J., Mason, A., Cassarino, M., Chan, J., & Setti, A. (2021). Older Women's Experiences of a Community-Led Walking Programme Using Activity Trackers. *International Journal of Environmental Research and Public Health*, *18*(18), 9818. https://doi.org/10.3390/ijerph18189818

Presented as O'Brien, Jessica, Mason, Amy, Cassarino, Marica, Chan, Jason & Setti, Annalisa. (2021, 11-12 November). *'Using activity trackers to promote older people's outdoor activities – A community-led programme in Cork City'*.: Psychology Society of Ireland Annual Conference.

O'Brien, J., Mason, A., Cassarino, M., Chan, J., & Setti, A. (14 May 2021). *Using activity trackers to promote older people's outdoor activities – A community-led programme in Cork City*: Psychology Society of Ireland, Psychology, Health and Medicine Annual Conference.

Appendix B (Chapter Two)

Search Strategy for Separate Database searches

Pubmed: (((((((((((((((((((((((((((((((((multisensory integration[Title/Abstract]) OR multisensory function[Title/Abstract]) OR multisensory interaction[Title/Abstract]) OR multisensory binding[Title/Abstract]) OR multisensory perception[Title/Abstract]) OR multisensory processing[Title/Abstract]) OR "temporal window of integration"[Title/Abstract]) OR "temporal binding window"[Title/Abstract]) OR cross-sensory integration[Title/Abstract]) OR cross-sensory binding[Title/Abstract]) OR cross-sensory interaction[Title/Abstract]) OR cross-sensory processing[Title/Abstract]) OR cross-sensory perception[Title/Abstract]) OR cross sensory perception[Title/Abstract]) OR cross sensory integration[Title/Abstract]) OR cross sensory processing[Title/Abstract]) OR cross sensory interaction[Title/Abstract]) OR cross sensory binding[Title/Abstract]) OR cross modal perception[Title/Abstract]) OR cross modal integration[Title/Abstract]) OR cross modal binding[Title/Abstract]) OR cross modal processing[Title/Abstract]) OR cross-modal perception[Title/Abstract]) OR cross-modal processing[Title/Abstract]) OR cross-modal integration[Title/Abstract]) OR cross-modal binding[Title/Abstract]) OR bimodal integration[Title/Abstract]) OR multimodal integration[Title/Abstract]) OR cross-sensory integration[Title/Abstract]) OR cross-sensory perception[Title/Abstract]) OR cross-sensory processing[Title/Abstract]) OR perceptual training[Title/Abstract] OR *sensory perceptual learning[Title/Abstract] OR *modal perceptual learning[Title/Abstract] AND (Humans[Mesh] AND (adult[MeSH] OR adult[MeSH:noexp] OR aged[MeSH])))) AND (((((((intervention[Title/Abstract]) OR training[Title/Abstract]) OR train[Title/Abstract]) OR reduc*[Title/Abstract]) OR improv*[Title/Abstract]) OR rehab*[Title/Abstract]) OR program*[Title/Abstract] AND (Humans[Mesh] AND (adult[MeSH] OR adult[MeSH:noexp] OR aged[MeSH]))

Filters applied: Humans, Adult: 19+, Adult: 19-44, Adult: 65+

Web of Science: TS = multisensory integration OR multisensory function OR multisensory interaction OR multisensory binding OR multisensory perception OR multisensory processing OR perceptual learning OR cross-modal perception OR cross-modal integration OR cross modal perception OR cross modal integration OR intersensory perception OR intersensory integration OR cross-sensory processing OR cross sensory processing OR bimodal integration OR multimodal integration OR intersensory processing OR cross-sensory binding OR cross sensory binding OR cross-modal binding OR cross modal binding

AND TS = intervention OR training OR train OR reduc* OR improv* OR rehab* OR program*

NOT AB = child* OR adolescen* OR animal OR infant

AND AB = adult OR adults AND Language (English)

Scopus: (TITLE-ABS ("multisensory integration") OR TITLE-ABS ("multisensory perception") OR TITLE-ABS ("multisensory processing") OR TITLE-ABS ("multisensory interaction") OR TITLE-ABS ("multisensory binding") OR TITLE-ABS ("multisensory function") OR TITLE-ABS ("cross modal binding") OR TITLE-ABS (

"cross modal integration") OR TITLE-ABS ("cross modal perception") OR TITLE-ABS ("cross modal processing") OR TITLE-ABS ("cross-modal perception") OR TITLE-ABS ("cross-modal integration") OR TITLE-ABS ("cross-modal binding") OR TITLE-ABS ("cross-modal processing") OR TITLE-ABS ("cross-sensory perception") OR TITLE-ABS ("cross-sensory integration") OR TITLE-ABS ("cross-sensory processing") OR TITLE-ABS ("cross-sensory binding") OR TITLE-ABS ("cross sensory integration") OR TITLE-ABS ("cross sensory perception") OR TITLE-ABS ("cross sensory processing") OR TITLE-ABS ("cross sensory binding") OR TITLE-ABS ("intersensory processing") OR TITLE-ABS ("intersensory integration") OR TITLE-ABS ("multimodal integration") OR TITLE-ABS ("multimodal binding") OR TITLE-ABS ("bimodal integration") OR TITLE-ABS ("bimodal perception") OR TITLE-ABS ("perceptual training") OR TITLE-ABS ("*modal perceptual learning") OR TITLE-ABS ("*sensory perceptual learning")) AND (TITLE-ABS (intervention) OR TITLE-ABS (train) OR TITLE-ABS (program*) OR TITLE-ABS (reduc*) OR TITLE-ABS (improv*) OR TITLE-ABS (rehab*)) AND NOT (TITLE (child*) OR TITLE (infant) OR TITLE (adolescen*) OR TITLE (animal))

PsychInfo: "multisensory integration" or "temporal binding window" or "window of integration" or "multisensory processing" or "multisensory interaction" or "multisensory function" or "multisensory perception" or "cross-modal perception" or "cross-modal integration" or "cross-modal binding" or "cross-modal processing" or "cross modal perception" or "cross modal integration" or "cross modal processing" or "cross modal binding" or "cross sensory binding" or "cross sensory integration" or "cross sensory perception" or "cross sensory processing" or "cross-sensory integration" or "cross sensory perception" or "cross sensory processing" or "cross sensory binding" or "multimodal perception" or "multimodal binding" or "multimodal integration" or "bimodal integration" or "bimodal perception" or "bimodal processing" or "perceptual training" or "*sensory perceptual learning" or "*modal perceptual learning" or "intersensory integration" or "intersensory perception" and intervention or program or training or rehab* or improv*

Filter applied: adulthood (ages 18 and over)

Table B.1
Overview of included studies

Authors	**Participants (sample size; age range; mean age (SD); percentage females)**	**Experimental intervention**	**Task**	**sensory modalities in training**	**control group**	**intervention session details**	**Outcome Task**	**outcome measurements**	**SOAs**	**Main findings**
Cecere, Gross & Thut, 2016	Healthy adults (30); Auditory-leading and visual-leading training (10; n.r.; 21.5; 70%); Only auditory-leading training (10; n.r.; 22; 30%); only visual-leading training (10; n.r.; 21.2; 50%)	2-AFC SJ task with feedback (across 3 SOAs within participant's estimated TBW) experimental groups: 1) trained on auditory-leading stimulus pairs 2) trained on visual-leading pairs 3) trained on both of above	Determine if stimulus pairs presented synchronously or asynchronously by pressing corresponding button	Audio-visual	None; 3 experimental groups	2 sessions x 2 consecutive days	2-AFC SJ task	D prime	+/- 50, 100, 150, 200, 250, 500 ms	Participants who received training on both auditory-leading and visual-leading stimulus pairs improved in sensitivity to visual-leading trials but not on auditory-leading trials. None of the training types improved sensitivity to detecting synchrony on auditory leading stimulus pairs
Virsu et al., 2008	University students (28; 20-41; 26.3 (4.8); 57.14%)	2-AFC SJ task using staircase procedure (3 stimulus pairs presented unimodally or bimodally– audio-visual, audio-tactile, visual-tactile)	Determine if stimulus pairs presented synchronously or asynchronously by pressing corresponding button	Auditory, visual, tactile, audio-visual, audio-tactile, visual-tactile	None	8 sessions, 2 per week across 2 months	2-AFC SJ task (with staircase)	Mean SOA threshold (ms) and practice gains (%)	Staircase procedure used	Mean SOA threshold improved from session 1 to follow-up at 7 months. Significant practice gains were seen on all bimodal tasks (audio-visual, audio-tactile, visual-tactile). Transfer of learning between modalities was not observed.

Kramer, Roder & Bruns, 2020	Healthy adults: (18; 19-39; 24.4 (n.r.); 77.78%)	Audio-visual task with in task visual feedback (speakers and laser points used as stimuli in room)	Localise auditory stimulus by using pointing device to select location	audio-visual, spatial	Repeated Measures: control conditions and unimodal blocks	4 sessions (not necessarily seperate days)	Audio visual spatial task	Ventriloquism effect	n/a	Magnitude of ventriloquism effect modulated by feedback such that reduced ventriloquism effect when feedback provided about position of auditory stimulus.
Theves et al., 2020	healthy adults: (14; 20-25; n.r. (n.r.); 71.43%)	2-IFC SJ Task with feedback	identify which pair of stimuli were synchronous	audio-visual	Repeated Measures: (1) training with feedback, (2) training without feedback, (3) exposure only	30-35mins x 1 day (SOAs: 50-250 ms)	2-IFC SJ Task with feedback (MEG measured during)	TBW	50 – 300 ms	1) Training with feedback significantly reduced the TBW (by on average 44%) 2) Training without feedback exhibited significant albeit smaller decreases in TBW. Exposure-group did not change in TBW. 3) The increase in temporal acuity was accompanied by elevated beta-band activity (over central and parietal sensors at 80-410 ms) following training.

O'Brien et al., 2017	community-dwelling older adults aged 60-81: open-skill exercise: 18;n.r.;69.22 (5.09);94.4%. Closed-skill exercise: 19; n.r.; 69.16 (4.8); 36.8%. Control group: 21, n.r.; 70.48; 61.9%	open-skill exercise vs. closed-skill exercise	engage in single bout of designated exercise type	n/a	Engaged in sedentary activity (active retired meeting/ card games)	open-skill: 80 +/- 20mins; closed-skill: 70 +/- 20mins; control: 60 mins	SiFI	(d’) in correctly perceiving two flashes with two beeps (hits) compared to perceiving two flashes in the illusion conditions (70, 150 and 230ms)		1) A single bout of open-skill exercise significantly improved SiFI performance (d’) 2) Neither a bout of closed-skill exercise or the control activity significantly affected SiFI performance (d’)

Merriman et al., 2015	community-dwelling older adults: intervention group: n = 38, 97.37% female: fallers: 17; n.r.; 74.06 (6.66); n.r. Healthy: 21; n.r.; 74.9 (8.97); n.r. Control group: n = 38, 60.53% female: fallers: 17; n.r.; 73.41 (7); n.r. Healthy: 21; n.r.; 74.33 (11.09); n.r.	Exergame balance training	use postural balance on Wii board to move target object on screen during gameplay	visuo-spatial	passive control group	5 weeks x (2 x 30 min sessions per week)	SiFI	Percent correct in illusory conditions (1 flash 2 beeps at SOA -70, -150, -230, 70, 150, 230 ms)		1) No evidence for a direct benefit of exergame intervention on SiFI performance 2) A trend for better performance for fall-prone older adults in the Intervention group was found, with improved task performance from pre- to post-assessment. 3) SiFI performance by the fall-prone older adults from the sheltered accommodation cohort were less correct than of other fall-prone participants or of healthy older adults living in sheltered accommodation (who shpwed task performance similar to community-dwellers).

De Niear, Noel & Wallace, 2017	young adults: 65, 18-28; 20.48 (n.r.); 55.38%. N = 25 in feedback group. N = 40 in control groups	SJ Task with feedback (+/- 400, 350, 300, 250, 200, 150, 100, 50 ms)	Judge whether audio and visual stimuli were synchronous or asynchronous	audio-visual	SJ task with no feedback (n = 15) vs. 20% false/erroneous feedback (n = 13) vs. 50% false/erroneous feedback (n = 12)	1 session x 90 mins	SJ task	1) TBW 2) point of subjective simultaneity	only SOAs of ±150, 100, 50, and 0 ms were utilized to fit distributions	1) Groups receiving feedback showed decreases in the absolute value of PSS over time. The control group (no feedback) did not see significant changes in PSS. 2) There was significant narrowing of the TBW for groups receiving feedback (between trials) as well as for the no feedback group. TBW narrowing occurred more rapidly for the feedback groups.

Holt et al., 2016 [RCT]	community-dwelling older adults: 60, 65+, 72.25 (6.5); 60%. N = 30 intervention, N = 30 control	One-to-one chiropractic care (usual care provided by practioners, included high-velocity, low amplitude, table assisted and instructor-assisted adjustment approaches)	specifics of care varied between participants, tailored to their needs	no specific sense targeted	attended usual healthcare appointments	12 weeks of chiropractic care, average no of visits = 21.9 (8.6), range 2-33	SiFI	Percent correct in illusory conditions	SOA 190ms	Receiving chiropractic care affected susceptibility to the SiFI, with the chiropractic group showing greater improvement than the control group across the 4- and 12-week assessments. The chiropractic group improved by 13.5% compared with control at 12 week assessment.

Alais & Cass, 2010	unpaid volunteers and study authors: (17; n.r.; n.r. (n.r.); n.r.).	TOJ	3 types of TOJ training: auditory only TOJ, visual only TOJ, audio-visual TOJ	auditory, visual, audio-visual	n/a	8 sessions completed over 8 -13 days, one session per day. Daily training consisted of an 80-trial adaptive staircase to estimate thresholds for onset TOJs	TOJ	temporal order onset discrimination thresholds	Targets were synchronous within modalities, but between modalities they were Asynchronous (2.5 Hz amplitude modulation of stimuli was 180 degrees out of phase between Modalities)	1) Robust TOJ learning was observed, including the audio-visual group who showed improved TOJ onset discrimination post-training. 2) Audio-visual TOJ training transferred to visual tasks (discriminating the order of visual onsets (purple column) but not auditory tasks. TOJ training on visual stimuli or on auditory stimuli did not exhibit any transfer.

O'Brien et al., 2020	community-dwelling older adults (23; 60-85; 74.17 (6.13); 43.47%. Young adults (20; 18-35; 24.2 (4.23); 55%.	2-IFC task with feedback	Determine which of 2 stimulus pairs occurred simultaneously (50 ms - 300 ms)	audio-visual	n/a	3 days consecutive training	SiFI, 2-IFC task	sensitivity analysis - d prime (SiFI), mean proportion of correct responses and TBW size (2-IFC)	SiFI: 70 ms, 110 ms, 150 ms, 230 ms. 2-IFC: 50, 100, 150, 200, 250, 300 ms.	Both older and younger adults showed significantly reduced TBW from pre- to post-training, as for the younger adult group. No change to perceptual sensitivity (SiFI task) for either group post-training

Stevenson et al., 2013	undergraduate students and university employees (22; n.r.; 22 (n.r.); 50%	Visual only TOJ with feedback	Participants presented with two white circles and asked to indicate which circle appeared first, the one on the top of the screen or the one on the bottom	visual	Visual only TOJ without feedback	5 days training	2-IFC SJ Task	TBW	−300 ms (auditory stimulus leading) to 300 ms (visual stimulus leading) at 50 ms increments including a 0 ms SOA condition in which both presentations were simultaneous for a total of 13 conditions	1) Visual TOJ training led to reduced TBW as measured using 2-IFC SJ task. Significant narrowing of TBW for visual-leading TBW, not for auditory. For control group, no significant changes seen for TBW size for whole, visual or auditory leading TBW. 2) Strong correlation between wide initial TBW and greater narrowing of TBW induced by visual training
Appiah-Kubi & Wright ,2019	young healthy adults (33: 10 control, 12 headshake + training, 11 no headshake +training;18-35; 24.5 (4.4); 45.5%)	Vestibular balance training (weight shifting exercises)	8 shifting exercises on force plate	vestibular	Non training control group	twice a day 3-4 hours apart every second day (Monday, Wednesday, Friday) for 1 week. 15 X 1 min exercises with physical therapist	Sensory Organisation Test (including visual-vestibular conditions; sensory ratio used to analyse sensory reweighting)	somatosensory ratio	n/a	1) Vestibular training (Headshake group) resulted in significant changes in postural control relative to the control and no headshake group (postural training without vestibular activation). 2) The Headshake group showed improvements in the somatosensory (SOM) ratio of the SOT, indicating somatosensory up-weighting for this training group. The no headshake group condition did not show significant

										changes from pre to post-training.
Zerr et al. 2019	university students and staff (45: 40 experimental, 5 control; 20-38; 22.6 (3.5); 62.5%)	SJ task with feedback (based on Powers et al., 2009 vs. unisensory training using visual flashes only and participants asked to judge their synchronicity)	SJ task from Powers et al., 2009 with feedback. SOA 0-150ms at 25ms intervals, visual-leading conditions only. Participants judge whether a visual and an auditory stimulus were presented synchronous or asynchronous	audio-visual	exposure to stimuli	3 day training (short group did 120 trials per day, long group did 360 trials per day)	SJ task, SiFI	TBW (SJ), percent fission illusion (SiFI)	SJ task: 0 - 250 ms at 25 ms increments; SiFI: 25 - 250 ms at 25 ms increments	1) AV training significantly narrows TBW more so than unisensory training. Effects persisted at 7 day follow up. Training length did not have any effect. 2) No significant effect of training on SiFI susceptibility.

Yang et al., 2018	Older adults: training group (13; 68-75; 70.7 (n.r.); n.r., control group (13; 65-78; 68.1 (n.r.); n.r. Young adults: training (13; 19-21; 20.1 (n.r.); n.r., control (13; 19-21; 20.5 (n.r.); n.r.	AV discrimination training	simultaneous or asynchronous presentation of visual and auditory stimuli in the same or different hemispace. Participants respond whether stimuli were synchronous or asycnhronous. SOAs: -300ms (auditory lead) to +300ms (visual lead) at 20ms intervals	audio-visual	no task in between EEG recordings	4 days per week for 4 weeks (10-20 mins sessions per day)	auditory oddball task, AV task	P300 ERP component (during oddball task)	AV task: (±300 ms, ±250 ms, ±200 ms, ±150 ms, ±100 ms, ±50 ms, 0 ms) in one block	1) Training had no effect on P300 component in young adults. P300 amplitudes significantly greater in older adults post-training vs pre-training. No difference in pre to post-test for control group of older adults. 2) AV task performance was significantly higher post-training vs pre-training for both older and younger adults. No change for control group.
Mc Govern et al., 2016	young adults (12; 18-35; 25 (n.r.); 50%)	2-IFC SJ task with feedback	2IFC AV with staircase procedure (3 down, 1 up), feedback in form of high or low pitch to indicate correct or incorrect response respectively, participants asked to indicate which pair synchronous	audio-visual	none	3 days of training	2 IFC SJ task	Same task as in Powers et al (2009; 2016) for n = 6 (temporal group); estimate of TBW based on ventriloquist effect of AV SOAs (temporal integration task), n = 6 (spatial group) estimate of TBW based on ventriloquist effect of visual locations (spatial integration task); 2 IFC spatial localisation test used,	(−800ms, −400ms, −200ms, −100ms, 0ms, 100ms, 200ms, 400ms, 800ms)	Perceptual training resulted in narrowing of TBW (near 50% reduction). Training did not narrow window of spatial integration (irrelevant to review as unisensory integration.)

								discriminate position of auditory bursts while ignoring irrelevant visual information		
De Niear et al., 2018	young adults (28; n.r.; 20.61 (n.r.); 50%)	Flash beep' training (n = 8) vs AV speech training (n = 9)	Flash-beep: judge whether visual and auditory stimuli synchronous or asynchronous and respond with corresponding key. AV speech stimuli in place of beep sound (video of speaker and spoken sound). SOAs: 150, ± 100, ± 50 and 0 ms	audio-visual	AV speech exposure group (n = 9) involving visual detection task instead of SJ	4 days of training	SJ task	TBW	± 400, ± 300, ± 250, ± 200, ± 150, ± 100, and ± 50	1) Perceptual training was effective at improving temporal acuity for each group but benefits specific to trained task; flash beep group did not change in acuity to AV speech task and vice versa for AV speech training group. Flash beep task improvement in TBW (narrower) was sustained at 1 week follow-up. Control group saw no narrowing of TBW.

De Niear, Koo & Wallace, 2016	typically developing adults (51; n.r.; 20.21 (n.r.); 54.9%)	2-IFC SJ training	2IFC SJ task with feedback 3 training groups (easy, moderate and difficult based on SOAs used). SOAs were individually determined based on performance for the pre-training SJ assessment. Easy = easily detect synchrony, moderate = chance level, difficult = rarely detect synchrony	audio-visual	none	1 day of training	2 IFC SJ task (as in Powers et al.,2009; 2016)	TBW	each SOA (±400, 300, 250, 200, 150, 100, 50, and 0 ms) was randomly presented 20 times (total of 300 trials) for each assessment	1) TBW narrowing only significantly occurred in the 'difficult' training group, 'easy' and 'moderate' group did not significantly reduce TBW post-training. 2) The 'easy' training protocol impaired temporal acuity with enlarged TBW seen post-training

Mozolic et al., 2011	older adults (66; 65-75; 69.4 (n.r.); 53.03%)	Visual and Auditory selective attention training	Four task categories: (A) visual tasks with visual distractors, (B) visual tasks with auditory distractors, (C) auditory tasks with auditory distractors, and (D) auditory tasks with visual distractors. For each, tasks included detecting, identifying, classifying, and/or sequencing visual or auditory letters, words, and numbers. Simple mathematical operations (addition or subtraction)	audio-visual	Attended 30 minute educational lecture series focused on topics in healthy aging	8 weeks of training for 1 hour each week (total training time = 8 h)	Cued discrimination paradigm: participants choose between red and blue during different attention conditions. Stimuli presented in either the auditory, visual or simultaneously in both modalities.	mean responses on multisensory trials	n/a	Attention training resulted in significant reductions in integration during selective auditory and selective visual attention. No change in integration during divided attention. The control group had no significant changes in integration during any attention condition.

Setti et al., 2014	older adults (34); experimental group (24; 61-86; 72.75 (6.3); 54.17%). Control group (10; 70-83; 75.8 (4.4); 60%)	AV TOJ task with feedback	auditory beep and visual flash presented and participants asked to judge which stimuli was presented first. Feedback given after each trial 'correct response' or 'incorrect response' and staircase procedure used. SOAs: 30 - 590 ms at 40 ms intervals, staircase procedure used	audio-visual	Control group completed control psychophysics task, similar stimuli as experimental task, no feedback given and no staircase procedure used.	5 day consecutive training x 30 mins	SiFI, TOJ training task	SiFI: proportion correct on illusory conditions and sensitivity analysis (d prime), TBW	30, 70, 110, 150, 190, 230, 270 ms	1) Participants who successfully trained on the TOJ task displayed reduced SiFI susceptibility post-training. 6 of 24 experimental group did not train. d' improved for successfully trained participants (approached significance at 0.055). 2) Correlation found between TBW post-training and SiFI susceptibility, such that TBW size predicts susceptibility.
Surig, Bottari & Roder, 2017	young adults (21; 21-37; 26 (n.r.); 42.86%). Experimental: n = 11, control: n = 10.	2-AFC SJ Task with increasing difficulty (with feedback)	Judge whether the AV stimulus was presented synchronously or asynchronously. SOAs: min +/- 20 ms, max = +/- 300 ms at 50 ms intervals. (SOAs at increasing difficulty, SOA chosen based on preceding 20 trials)	audio-visual	SJ task with random difficulty (SOAs chosen randomly)	5 sessions across 10 days, max 1 session per day	Spatial localisation task, Redundant Target Task	Ventriloquist effect (localisation task), reaction times (redundant target task)	Localisation task inter-trial intervals: 1500 - 2500 ms. Redundant Target Task: +/- 15, 30, 60, 100, 200 ms.	1) Faster learning observed in the experimental group vs. the control. Training effects transferred to both the spatial ventriloquist effect and the redundant target task for the experimental group only

Pantev et al., 2015 (Experiment 4)	non-musician adults (24; n.r.; 26.45 (4.25); 70.83%. Experimental n= 12, control n = 12	Audio-visual music reading training	Participants presented with video comprising auditory (melodies) and visual stimuli (image showing height of note images representing the pitch height of each tone in a simplified music reading modus). Participants asked to discern if video was congruent or incongruent.	audio-visual	AV task using same stimuli but presented in separate blocks of visual (disks) and auditory (tones) stimuli. Task was to detect if standard or deviant stimuli within one modality	5 training sessions within 7 days, 28 mins per session	Same as training task but new melodies to avoid training effect.	MEG of activity in auditory cortex (during task completion) - Brodmann areas 41 and 42	n/a	1) The experimental training group (required the integration of auditory and visual info) resulted in a neuroplastic effect in the auditory cortex that was correlated with AV processing, it showed no effect in unisensory processing. 2) The control group that required processing auditory and visual information independently resulted in a neuroplastic effect in the auditory cortex that affected auditory processing, it showed no effect in AV integration.
Powers, Hillock & Wallace, 2009	Experiment 1: undergraduate students (22; n.r.; 20.73 (n.r.); 50%). Experiment 2: undergraduate/graduate students (23; n.r.; 20.20 (n.r.); 56.52%)	Experiment 1: 2-AFC training. Experiment 2: 2-IFC training	Experiment 1: respond if a single pair of AV stimuli were presented simultaneous or non-simultaneously. Experiment 2: respond which of two pairs of AV stimuli were presented simultaneously. (SOAs: -300 ma to 300 ms at 50 ms increments).	audio-visual	2-AFC exposure: oddball task using same stimuli (SOAs: -150 ms to 150 ms in 50 ms increments.	5 days x 1 hour	Training task itself	a) Grand mean score on each SOA b) TBW	SOA: -300 ms to 300 ms at 50 ms increments	1) Experiment 1: A significant reduction in TBW after 1 day of 2-AFC training compared to baseline. TBW did not significantly change following further training days. At 1 week follow up, TBW size was significantly smaller than at baseline and than after 1 day of training but not significantly different to TBW post-training day 5.

										Control group displayed a significant increase in TBW from baseline to post-training day 4. Significant decreases in mean probability judgment (grand means) were seen at the 100 ms 150 ms and 200 ms after 5 days of 2-AFC training. 2) Experiment 2: TBW was found to significantly reduced following one day of 2-IFC training. TBW size at 1 week follow up was significantly smaller than at baseline or at post-training assessment day 5.
Powers et al., 2016	university students (56): 2-IFC group = (20; n.r.; 20.3 (n.r.); 70%. 2-AFC group = (22; n.r.; 20.73 (n.r.); 50%. Control = (24; n.r.; 19.5 (n.r.); 28.57%)	2-IFC SJ task with feedback vs. 2-AFC SJ task with feedback	2-IFC task: judge whether stimuli were simultaneous or not. 2-AFC task: select which pair of stimuli were simultaneous	audio-visual	2-AFC exposure task (oddball task using same stimuli as 2-AFC)	5 days x 1 hour	SiFI	d prime/ TBW	SOA: +/- 50 - 300 ms by 50 ms increments	No overall improvement in SiFI performance but improved visual acuity post training (2 flash conditions)
Rosenthal, Shimojo & Shams, 2009	adults: Experiment 1 (15; 22-33; n.r. (n.r.); 50%. Experiment 2 (6; 23-40; n.r. (n.r.); 62.5%). Experiment 3 (6 ; 20-33 ; n.r. (n.r.); 50%)	SIFI with feedback (Experiment 1 & 2) ; SiFI with feedback and monetary incentive - up to $40 (Experiment 3)	Decide if one or multiple flashes presented and rate confidence of judgement (high or low)	audio-visual	N/A (Repeated Measures design – feedback and no feedback block of trials)	1 hour	SiFI	d prime	SOA 57 ms	1) Providing feedback to participants did not affect SiFI susceptibility, except when a monetary reward was offered for correct performance.

										2) No correlation found between feedback block placement and task performance (no difference if feedback block presented first or second)
McGovern et al., 2022	young adults: (21; 19-31; 23 (3.18); 61.9%. older adults: (20; 65-85; 71 (5.74); 55%).	2-IFC SJ Task with feedback	Judge which of 2 AV pairs were presented simultaneously	audio-visual	N/A	N/A	SiFI	TBW	SOA +/- 400, 200, 100, 50, 25	1) Improved discrimination thresholds on 2-IFC task following training for both age groups 2) Reduced susceptibility to SiFI fission and fusion illusions for both age groups. 3) Significant narrowing of TBW for both age groups when based on fission illusion, but only for young when based on fusion illusion
Huang et al., 2021	Training group; (26; n.r.; 21.58 (1.72); 57.69%). Control group: (28; n.r.; 21.48 (1.99); 60.71%).	SiFI with feedback	Report number of visual flashes	audio-visual	Control group did not receive training	7 sessions across 7 days	SiFI		Fission illusion (77 ms); fusion illusion (66 ms)	1) Training resulted in reduced susceptibility to fusion and fission illusion. 2) Compared to control group, training group displayed reduced susceptibility to fission illusion, *Cohen's d* = 1.12 but not on fusion

										illusion at post-test). 3) A linear trend for improvement across training days was observed with pattern of stabilisation after day 5
Horsfall, Wueger & Meyer, 2021	young adults (32; 18-28; 21.03 (2.44); 71.88%.	2-AFC SJ task with feedback (in form of auditory beeps): 2 groups, bright stimuli group (n = 11) vs. dim stimuli group (n = 10)	Judge whether stimuli pairs presented synchronously or asynchronously	Audio-visual	n/a	Single session	2-AFC SJ task	TBW	SOA +/- 300, 200, 150, 100, 50, 0	1) Training using bright stimuli led to reduced TBW using bright stimuli. Group trained with dim stimuli did not see reduction in TBW post-training 2) Training on bright stimuli did not transfer to performance on dim stimuli, with no effect on TBW

Note. AV = audio-visual; EEG = electroencephalogram; ERP = Event Related Potential; MEG = Magnetoencephalogram; ms = milliseconds; *n*.r. = not reported; SiFI = Sound-induced Flash Illusion; SJ = Simultaneity Judgement; SOA = Stimulus Onset Asynchrony; TOJ = Temporal Order Judgement task; TBW = Temporal Binding Window; 2-AFC = 2-Interval Alternate Forced Choice Task; 2- IFC = 2 Interval Forced Choice Task.

Appendix C: Chapter Three (Study One)

Table C1

Group means on unisensory conditions of the SiFI at pre-training (standard deviation in parentheses)

Condition	Older	Younger	P value
1-flash	0.99 (0.04)	1 (0)	0.35
1-beep	0.98 (0.10)	1 (0)	0.35
2-beeps SOA 70 ms	0.8 (0.36)	1 (0)	0.02*
2-beeps SOA 110ms	0.93 (0.18)	0.98 (0.11)	0.67
2-beeps SOA 150 ms	0.96 (0.14)	0.95 (0.15)	0.89
2-beeps SOA 230 ms	0.98 (0.10)	1 (0)	0.35
2-flashes SOA 70 ms	0.48 (0.29)	0.71 (0.35)	0.015*
2-flashes SOA 110 ms	0.8 (0.19)	0.88 (0.21)	0.09
2-flashes SOA 150 ms	0.91 (0.13)	0.99 (0.04)	0.007*
2-flashes SOA 230 ms	0.93 (0.11)	1 (0)	0.004*

Note. P value represents results from Mann-Whitney U tests. * denotes a significance difference at $p < 0.05$.

Figure C1

Graph representing calculation of Temporal Window of Integration (TWI) for one participant. Participant data on 2-IFC task at pre-training is fitted with a 3rd order polynomial probability curve to calculate estimated window size. 126.10 ms is width of window for participant below. Black lines mark the point halfway between the participant's lowest accuracy score and 100% (i.e. 75%)

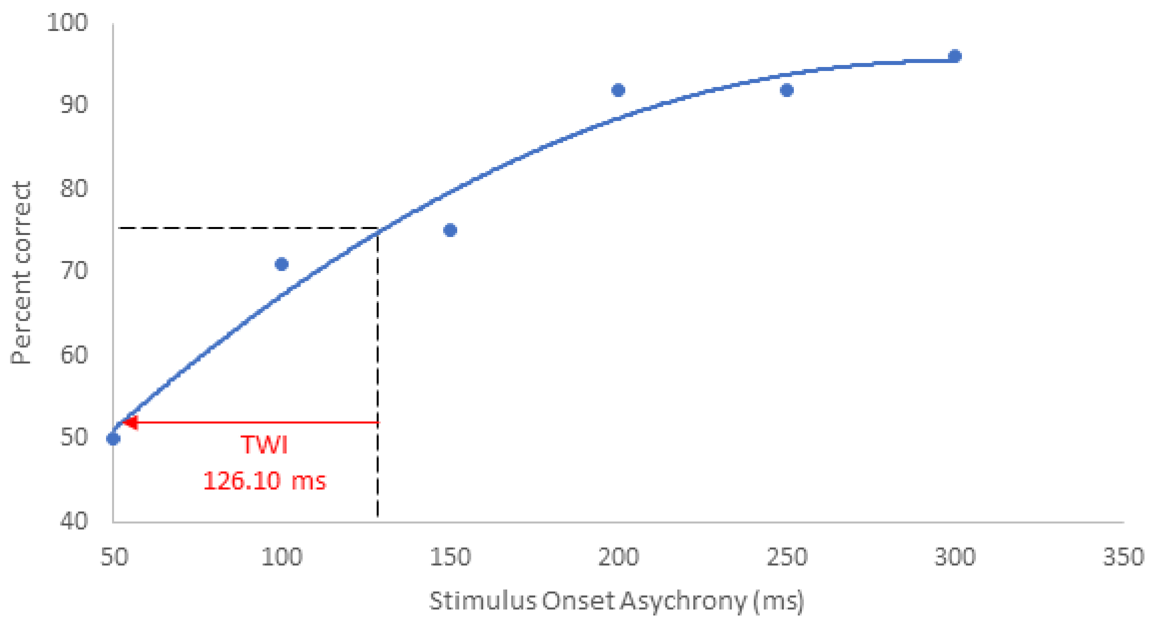
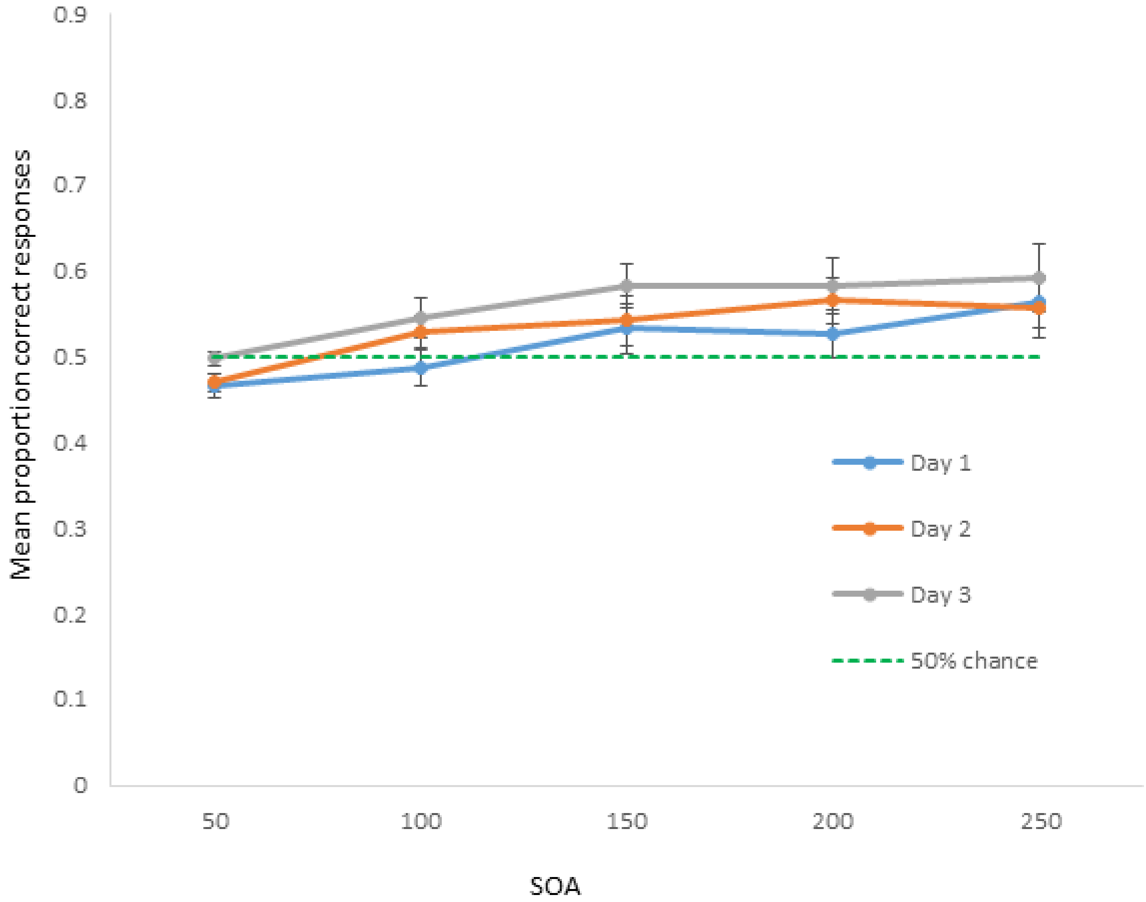


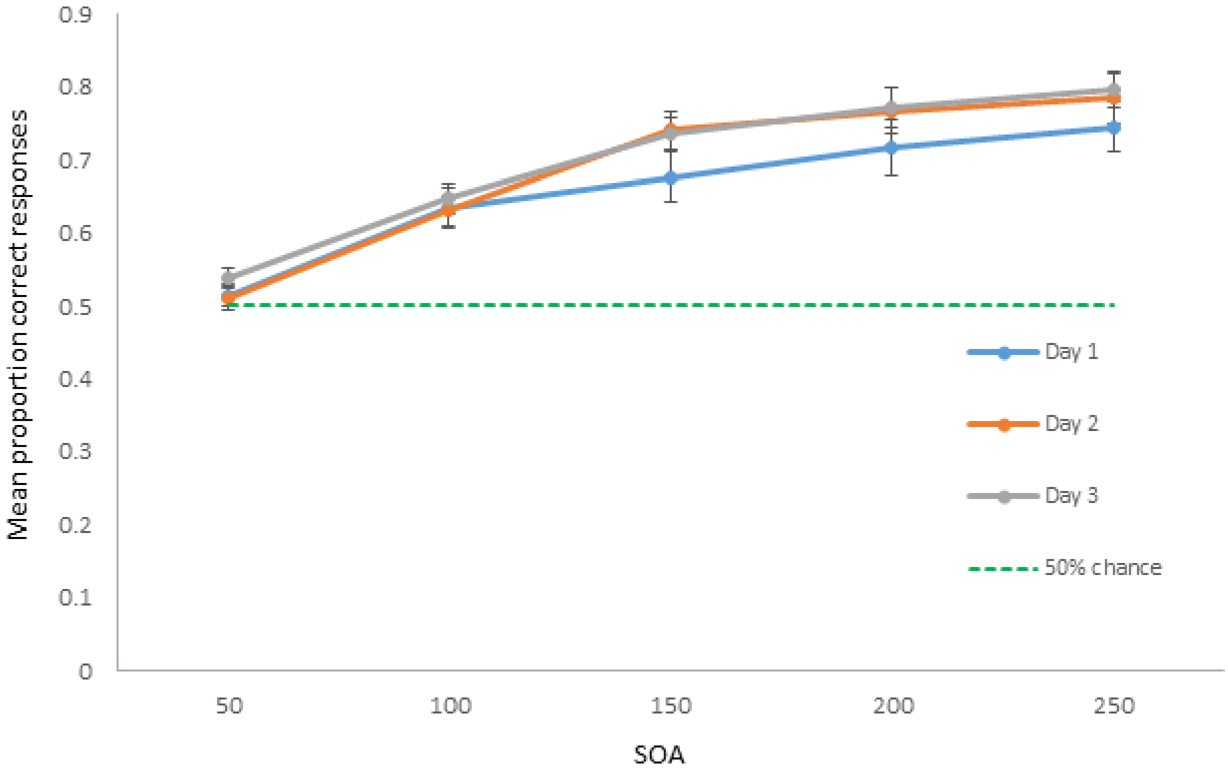
Figure C2

*Mean proportion of correct responses per SOA in each day of 2-IFC training for the older (**A**) and younger (**B**) groups*

A)



B)



Data Sheet C1: Data and results for asynchronous training group

A sample of 20 community-dwelling older adults (*M* = 70.56, *SD* = 6.07) were tested on a variation of the perceptual training used in the current study. This additional group were labelled the Asynchronous group. They completed the same pre- and post-training measures as our older and young adult groups but their training protocol was slightly different. Instead of being asked to identify the simultaneity of stimuli, participants were asked to identify which stimulus pair were presented asynchronously. They also received feedback during this training.

Rationale

It is important to note that there are potentially substantial differences between the paradigms successfully utilised with young adults (Powers et al., 2009; 2012), and the partially successful one with older adults (Setti et al. 2014). The former is based on a simultaneity judgement (SJ), while the latter is based on a temporal order judgement. In two studies (Basharat et al., 2018; Bedard and

Barnett-Cowan, 2016), the audio-visual SJ was found to be easier for older adults than the TOJ task, as indicated by a narrower TWI in the SJ task than in the TOJ task. In addition, neither the TOJ or SJ were related to the susceptibility to the stream-bounce illusion (Bedard and Barnett-Cowan, 2016). Simultaneity and temporal order may in fact be implemented by different brain networks (Basharat et al., 2018), different processes, and response biases are thought to underlie the two types of tasks (Spence and Parise, 2010). The crucial differences can reside in participants' attention or their decision-making process in relation to task demands (García-Pérez and Alcalá-Quintana, 2012). The question arises whether one could utilise the same SJ perceptual stimuli, and direct participants' attention to the temporal discrepancy, instead of the synchrony, with differential training effects.

Method

The pre-training and post-training measures were identical to that of the main experiment. However, the instructions during training differed for this asynchronous group. Instead of focusing on the synchrony of stimuli, participants were tasked with identifying the stimulus pair in which the stimuli were presented asynchronously (i.e. were not presented simultaneously). Descriptive characteristics of this sample compared to our older adult experimental group (i.e. synchronous training) are presented in Table S1.

Table C2

Descriptive characteristics per older training group

	Synchronous	Asynchronous	p value
N	23	20	
Age	74.17 (6.28)	70.56 (6.07)	0.07
Gender	M: 13 (56.52%), F: 10 (43.48%)	M: 3 (15%), F: 15 (85%)	0.01*
SMMSE	28.67 (1.46)	28.4 (1.96)	0.69
IPAQ	4632.67(4331.63)	2996.69 (2405.31)	0.18
Fallers (*n*)	11 (42.85%)	12 (51.85%)	0.55

Note. Standard deviation in parentheses. * denotes significance at p<.05

Analysis

A three-way Mixed ANOVA was performed on the mean scores on the 2-IFC task, with Time (pre-training, post-training) and SOA (50 ms, 100 ms, 150 ms, 200 ms, 250 ms, 300 ms) as the within-participants factors, and Training Group (sync, async) as the between-participants factor. The ANOVA revealed no significant main effects of Time [$F(1, 41) = 2.79$, $p = 0.1$, $\eta_p^2 = 0.06$] or Training Group [$F(1,41) = 1.07$, $p = 0.31$, $\eta_p^2 = 0.03$]. There was a significant main effect of SOA [$F(3.41, 139.94) = 14.07$, $p < .001$, $\eta_p^2 = 0.26$]. Simple contrasts revealed participants performed significantly poorer at the shortest SOAs (50 ms, 100 ms, 150 ms) compared to the longer SOAs ($p < 0.05$) as would be expected. None of the two-way interactions were significant [Time × Group: $F(1, 41) = 2.32$, $p = 0.14$, $\eta_p^2 = 0.05$; Time x SOA: $F(3.78, 154.85) = 1.47$, $p = 0.22$, $\eta_p^2 = 0.04$; SOA x Group*:* $F(3, 205) = 0.47$, $p = 0.8$, $\eta_p^2 = 0.01$] nor was the three-way interaction [$F(5, 205) = 0.27$, $p = 0.93$, $\eta_p^2 = 0.07$].

A three-way Mixed ANOVA was performed on the mean *d'* scores for the SIFI task, with Time (pre-training, post-training) and SOA (70 ms, 110 ms, 150 ms, 230 ms) as the within-participants factors and Training Group (sync, async) as the between-participants factor. The ANOVA revealed no significant main effects of Time [$F(1, 41) = 1.41$, $p = 0.24$, $\eta_p^2 = 0.03$] or Training Group [$F(1,41) = 0.96$, *p* = 0.33, η_p^2= 0.02]. There was a significant main effect of SOA [*F*(2.48, 101.74) = 5.45, *p* = 0.003, η_p^2= 0.12]. Simple contrasts revealed participants performed significantly better at the longest SOA (230 ms) compared to the three shorter SOAs ($p < 0.05$). This is in line with expectations of greater integration (i.e. poorer perceptual sensitivity) at shorter SOAs. None of the two-way interactions were significant [Time × Group: *F*(1, 41) = 1.47, *p* = 0.23, η_p^2= 0.04; Time x SOA: *F*(3, 123) = 0.88, *p* = 0.46, η_p^2 = 0.02; SOA x Group: *F*(3, 123) = 0.29, *p* = 0.83, η_p^2= 0.07] nor was the three-way interaction [*F*(3, 123) = 0.06, *p* = 0.98, η_p^2= 0.01].

Conclusion

Neither a synchronous nor asynchronous training protocol was effective for training audio-visual discrimination efficiency or multisensory perception in healthy older adults. In relation to the manipulation of the instructions to focus participants' attention on the synchrony or a-synchrony of the stimuli, we found no effects of task. Therefore, the simple shift of task demands towards temporal discrimination, with a stimulus that is identical to the Simultaneity Judgement Task (SJ), did not produce any behavioural difference from the traditional SJ. This is in line with the literature indicating that TOJ and SJ are tapping into different processes and therefore an a-synchronicity judgement training is still behaviourally undistinguishable from a SJ in terms of its performance benefits or lack of thereof (García-Pérez and Alcalá-Quintana 2012).

References

Basharat, Aysha, Meaghan S. Adams, William Richard Staines, and Michael Barnett-Cowan Barnett-Cowan. (2018). 'Simultaneity and Temporal Order Judgments Are Coded Differently and Change with Age: An Event-Related Potential Study'. Frontiers in Integrative Neuroscience 12: 15.

Bedard, Gillian, and Michael Barnett-Cowan. (2016). 'Impaired Timing of Audiovisual Events in the Elderly'. Experimental Brain Research 234 (1): 331–340.

García-Pérez, Miguel A., and Rocío Alcalá-Quintana. (2012). ‘On the Discrepant Results in Synchrony Judgment and Temporal-Order Judgment Tasks: A Quantitative Model’. Psychonomic Bulletin & Review 19 (5): 820–846.

Powers, Albert R., Matthew A. Hevey, and Mark T. Wallace. (2012). ‘Neural Correlates of Multisensory Perceptual Learning’. Journal of Neuroscience 32 (18): 6263–6274.

Powers, Albert R., Andrea R. Hillock, and Mark T. Wallace. (2009). ‘Perceptual Training Narrows the Temporal Window of Multisensory Binding’. The Journal of Neuroscience 29 (39): 12265–12274.

Setti, Annalisa, John Stapleton, Daniel Leahy, Cathal Walsh, Rose Anne Kenny, and Fiona N. Newell. (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, Charles, and Cesare Parise. (2010). ‘Prior-Entry: A Review’. Consciousness and Cognition 19 (1): 364–379.

Appendix D: Study Four - Qualitative Interview Schedule

Hello ________________, I'm interested in hearing about your experience of dealing with falls and how you found participating in the recent UCC research project on falls and the brain. We're contacting those who took part in the research to hear about their experience and receive some feedback from you as a participant.

Verbal consent

Before we start, I want to confirm you are happy to participate in this phone interview. Your participation is voluntary and you do not have to answer all or any of these questions. You can stop the interview at any time. The interview should take approximately 30 minutes of your time. I will be recording this phone call so that I can listen back to it and write down our conversation for research purposes. I want to assure you that I will then delete this audio recording and no-one else will hear it. Do you consent to participate in this interview and have the interview recorded for research purposes?

When you're ready I'll start with the first question.

Opening question/building rapport:

How have you been since finishing the Falls Classes at the Hospital?

Topic 1: Falls

1. **Can you tell me about where you feel most comfortable, where you feel most steady on your feet?**
   Probes:
   environmental factors: what is it about this space/place that makes you feel confident in your balance or steadiness?
2. **A) I'm interested in learning about when you feel unsteady on your feet or feel like you may fall. Could you describe to me a situation(s) where you feel unsteady?**
   Probes:
   - indoor vs outdoor environments, home vs community setting.
   -In a typical week, is there any time you feel you might fall or lose your balance?
   B) Have you recently experienced a situation where you fell or almost lost your balance, for example in the last year? Can you tell me about this?
   (If no, ask about the last time they had a fall or lost their balance).
   Probes:

- What do you think might have caused the fall/loss of balance?
- Can you describe the environment you were in? (e.g. lighting, were other people around you?)
- Were you in the middle of doing something? (e.g. talking to someone, going somewhere?)

3. **You recently completed a 6 week Falls Class at the Hospital. Have you been doing anything differently since completing the classes?**

Probes:

- anything different to your daily routine
- have you seen a change in your confidence levels?
- Have you joined any other classes/groups since?

Topic 2: EEG Research Study

You were also a participant in our research study on falling, balance and the brain. I'd like to ask you a few questions to get your feedback on this study.

4. **First of all, thank you for participating in that research experiment. Can you tell me why you agreed to participate in the research at the Hospital?**

5. **You may remember we asked you to complete a computer task which involved flashes and beeps. You were asked to count the number of flashes onscreen and ignore the beep sounds.**

   Do you remember this test?
   If yes, how did you find this task?
   Probes: Did you find this task easy or difficult to complete?
   How did you feel after the task had finished?

6. **The research project used an EEG machine to measure your brain's electrical activity. This was the cap which involved wires and gel that you wore. The research project was looking at the brain and falls. How do you think there may be a link between the brain and falling?**

7. **What results would you like to get back from the research study?**
   Probe: how would you like to hear about this research? (e.g. what format – email, written report, diagram etc.)

8. **Can you think of something you would like to learn about falls? Is there something you think future research could focus on?**

9. **After taking part in this research project, what would you like to see done for people who fall?**

10. **How did you find the research sessions at the Hospital?**

    Probes: is there anything we could improve on?
    what might make it easier for others to take part in research like this?

Closing statement:

We have come to the end of our questions. I want to thank you very much for taking the time to answer these questions. We are excited to read through our interviews and get your feedback on your personal experience of falls and participating in a research project.

Have you any questions for me?

Is there anything else you'd like to mention?