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Age-related changes in the attentional modulation of multisensory integration in relation to balance maintenance

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ABSTRACT

Ageing is associated with increased multisensory integration and reduced attentional control during audiovisual processing, which can lead to inaccurate representations of dynamic environments and may contribute to fall risk in older adults. Alpha-band oscillatory activity (8–12 Hz), commonly interpreted as an index of inhibitory attentional control, is a plausible neural mechanism underlying age-related differences in multisensory attention. Here, we tested whether alterations in alpha oscillatory dynamics account for reduced attentional modulation of audiovisual integration in ageing, and whether these neural signatures relate to measures of fall risk.

Thirty-six younger adults (18–35 years) and thirty-six older adults (60–80 years) completed a cued spatial-attention stream–bounce task assessing audiovisual integration at validly and invalidly cued locations, with stimulus-onset asynchronies of 0 ms and 300 ms. Concurrent EEG was recorded to quantify task-related alpha-band activity as a marker of inhibitory control. Balance and postural sway were assessed as indices of fall risk.

Behaviourally, both age groups showed comparable attentional modulation of audiovisual integration. In contrast, electrophysiological data revealed age-related differences in neural control mechanisms: younger adults exhibited clear, cue-dependent modulation of alpha power, whereas older adults did not show such modulation. These findings demonstrate a dissociation between preserved behavioural performance and altered neural control mechanisms in ageing, highlighting the importance of neural measures for revealing age-related changes in attentional control that are not evident from behaviour alone. Together, these results implicate reduced flexibility of alpha-mediated inhibitory processes linking attentional control, multisensory processing, and balance in ageing.

1. Introduction

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

One potential reason behind increased fall risk in older adults are the age-related changes in multisensory integration. Multisensory integration describes the perceptual and cognitive mechanisms involved in binding sensory information together, to form a unitary percept of a person's body and environment (Stevenson et al., 2012 Talsma et al., 2010; Stein and Wallace, 1996; Diederich and Colonius, 2004). Research suggests that older adults display increased multisensory integration relative to younger adults (Pepper et al., 2023 Pepper and Nuttall, 2023 Laurienti et al., 2006; Peiffer et al., 2007; Mahoney et al., 2011). This increased integration has a positive outcome when the sensory information is congruent and should be integrated. For example, effectively utilising visual and auditory cues improves driving performance

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(Ramkhalawansingh et al., 2016) and speech perception abilities (see Jones and Noppeney, 2021, for a review). On the other hand, when task-irrelevant or incongruent information is erroneously integrated, this can have a negative outcome, producing representations of the environment that are confusing, noisy, and unstable (de Dieuleveult et al., 2017; Bedard and Barnett-Cowan, 2016). As such, the term "increased integration" refers to the erroneous binding of visual and auditory inputs that do not occur at the same time, or that is irrelevant to the task at hand.

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

One possible candidate mechanism for the age-related changes in attentional control during audiovisual integration may be the deployment of neural alpha oscillations. Despite historically being referred to as an "idling" rhythm associated with resting brain areas (Pfurtscheller et al., 1996; Lange et al., 2014), oscillatory alpha activity is now considered to index top-down attention (Bednar and Lalor, 2018; Wöstmann et al., 2017; Sauseng et al., 2005; Capotosto et al., 2012; Thut et al., 2006) and active inhibitory processes during sensory processing (Klimesch, 2012; Foxe et al., 1998). Crucially, increases in alpha power over parieto-occipital areas are associated with inhibition of sensory information, preventing it from being integrated into the percept (Keller et al., 2017; Keil and Senkowski, 2018). For example, O'Sullivan et al. (2019) found that during audiovisual speech perception, when the visual information was incongruent and had to be inhibited, alpha power increased in parieto-occipital brain regions. Increases in alpha power suppressed the processing of distracting sensory inputs, to prevent the integration of incongruent auditory and visual information (Kelly et al., 2006; O'Sullivan et al., 2019). At this point, it is important to note that much of the research into the functional role of oscillatory alpha activity has been conducted on younger adult participant groups; the increased difficulty that older adults have in ignoring distracting, irrelevant sensory information (Zhuravleva et al., 2014; Gazzaley et al., 2005) may be reflected in reduced alpha power compared to younger adults during a multisensory task in which irrelevant sensory information must be inhibited.

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

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

1) older adults will exhibit increased audiovisual integration compared to younger adults.
2) older adults will demonstrate weaker attentional control during audiovisual integration compared to younger adults.
3) older adults will demonstrate smaller increases from baseline in alpha power compared to younger adults.
4) balance ability will predict increased audiovisual integration and weaker attentional control during audiovisual integration

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

2. Methods

2.1. Participants

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

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

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

2.2. Pre-screening tools

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

2.2.1. Speech, spatial and quality of hearing questionnaire (SSQ; Gatehouse & Noble, 2004)

Participants rated their hearing ability in different acoustic scenarios using a sliding scale from 0–10 (0="Not at all", 10="Perfectly"). Whilst, at present, no defined cut-off score on the SSQ is available as a parameter to inform decision-making, previous studies have indicated that a mean score of <5.5 is indicative of moderate hearing loss (Gatehouse and Noble, 2004). As a result, people whose average score on the SSQ was lower than 5.5 were not eligible to participate in the experiment. This was to ensure that any changes in audiovisual integration measured in the task would not be due to a participant's inability to hear the auditory stimuli. Hearing acuity was then evaluated objectively using pure-tone audiometry (see Section 2.2.3) when participants attended the lab.

2.2.2. Informant questionnaire on cognitive decline in the elderly (IQ-CODE; Jorm, 2004)

Participants used a self-report version of the IQ-CODE (Jorm, 2004) to rate how their performance in certain tasks has changed compared to 10 years ago, answering on a 5-point Likert scale (1="Much Improved", 5="Much worse"). An average score of 3.65 is the usual cut-off point when evaluating cognitive impairment and dementia (Slade et al., 2023; Jansen et al., 2008), therefore people whose average score was higher than 3.65 were not eligible to participate in the experiment. This was to ensure that any changes in audiovisual integration measured in the task would not be due to the participant experiencing mild cognitive impairment.

2.2.3. Pure-tone audiometry

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

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

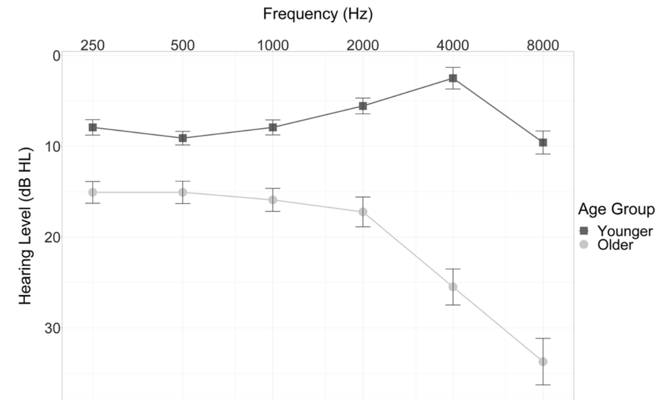

Fig. 1. Mean pure-tone audiometry thresholds recorded for each age group at each frequency. Black markers represent data of younger adults, grey markers represent the data of older adults. Standard error displayed as error bars.

Table 1
Mean scores on the *Speech, Spatial and Quality of Hearing Questionnaire* (SSQ), *Informant Questionnaire on Cognitive Decline in the Elderly* (IQ-CODE) and pure-tone audiometry (PTA) pre-screening measures, for both younger and older adults. Data is presented as mean (SD). Significance was set at a $p < .05$.

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

2.3. Experimental design

2.3.1. Questionnaire measures

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

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

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

2.3.2. Functional ability – the short physical performance battery (SPPB; Guralnik et al., 1994, 2000)

The SPPB (Guralnik et al., 1994, 2000) is divided into three sections measuring balance, gait speed and leg strength, each of which are scored from 0–4 and added together to provide a composite measure of functional ability. As a result, the minimum score on the SPPB was 0 points and the maximum score was 12 points. Lower scores on the SPPB are indicative of weaker lower-body functioning and an increased risk of falls (Guralnik et al., 2000). The stages of the SPPB are displayed in Fig. 2.

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

2.3.3. Timed up and go test (TUG; Podsiadlo & Richardson, 1991; Shumway-Cook et al., 2000)

As an additional dynamic measure of functional ability, participants were also asked to complete the Timed Up-And-Go (TUG) test (Podsiadlo and Richardson, 1991), which is a clinical assessment of fall risk in older adults. Participants are asked to stand from the chair, walk 3 m at a comfortable pace, turn around, walk back to the chair and sit down. The time that participants took to complete this assessment was recorded, with longer times (greater than 13.5 s for community-dwelling older adults; Shumway-Cook et al., 2000) indicating increased fall risk.

2.3.4. The stream-bounce task

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

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

The experiment consisted of 12 different trial conditions, randomised across all participants. The experimental block contained of a set of 60 validly-cued trials and a set of 60 invalidly-cued trials (two conditions), which were equally distributed between each side of the screen (left/right) and three stimulus onset asynchrony (SOA) conditions (Visual Only [VO], 0 milliseconds and 300 milliseconds); this means that each participant completed 120 valid trials and 120 invalid trials for each SOA. Participants completed the experiment in a quiet room on an Apple Mac computer (version 12.2.1) with a standard keyboard. All participants wore EEG-compatible earphones (ER2 ultra-shielded insert earphones; Intelligent Hearing Systems). A volume check was conducted at the beginning of the experiment; participants were presented with a constant tone and the volume of this tone was adjusted to a clear and comfortable level. Screen captures of a validly-cued, 0 ms SOA trial are displayed in Fig. 3. The percentage of "Bounce" responses provided in each Cue x SOA condition was calculated for each participant. The proportion of "Bounce" responses produced in Visual-Only conditions was subtracted from the proportion of "Bounce" responses produced in 0 ms and 300 ms conditions, respectively, such that behavioural "Bounce" data reflect the effect of multisensory processing.

2.3.5. EEG data acquisition and pre-processing

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

Processing and EEG analyses were completed offline using the EEGLAB toolbox (Delorme and Makeig, 2004) and MATLAB scripts. The

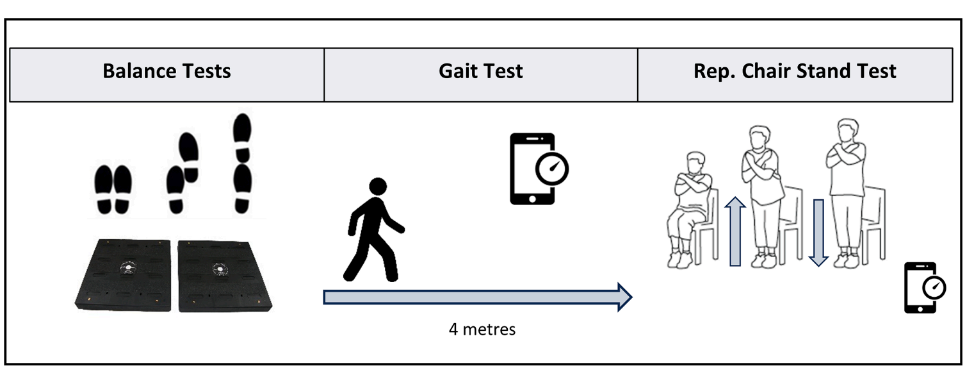

Fig. 2. Diagram depicting each assessment within the Short Physical Performance Battery (SPPB). Adapted from Tonet et al. (2023) and www.physio-pedia.com. Participants first completed the balance tests, standing on force platforms in side-by-side, semi-tandem and tandem stances for 10 s each. Participants then completed the gait test, in which the time taken to walk 4 m was recorded. Finally, participants completed the chair stand test, in which the time taken to sit down and stand up 5 times was recorded.

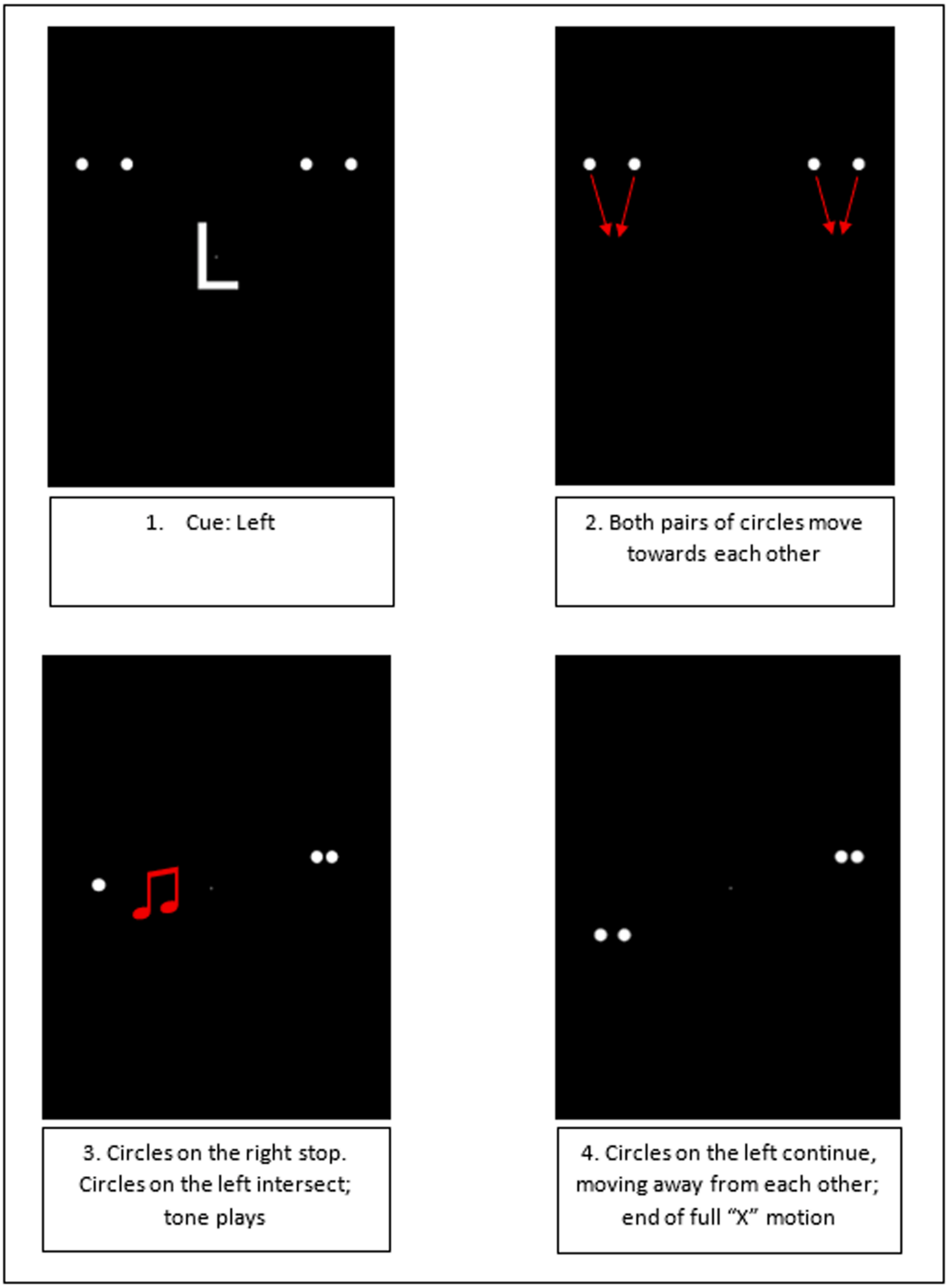

Fig. 3. Screen captures of a validly-cued trial (valid left), with an SOA of 0 ms (sound synchronous with intersection). Participants provided their pass/bounce judgement at the end of the trial. Image taken from the published manuscript of Pepper et al. (2023).

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

2.3.6. Alpha power extraction

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

$$Percent\ Change = \frac{alpha\ power_{task} - alpha\ power_{baseline}}{alpha\ power_{baseline}} \times 100$$

Finally, Percent Change produced in Visual-Only conditions were subtracted from Percent Change produced in 0 ms and 300 ms multisensory conditions, such that alpha data specifically reflect the effect of multisensory processing. This value is the alpha power value used in each statistical model.

The procedure outlining the entirety of the study is displayed in Fig. 4.

2.4. Statistical analyses

Two multiple linear regression models were run to examine whether a) age, oscillatory alpha power and balance ability and the interactions of each variable with age can predict audiovisual integration in the stream-bounce task (Model 1: Proportion of "Bounce" responses = Age + Cue + SOA + Alpha power + Sway Velocity + SPPB Score + Pure-tone audiometry + Age*Cue + Age*Alpha + Age*Velocity + Age*SPPB Score), and b) age, audiovisual integration and balance ability and the interactions of each variable with age can predict oscillatory alpha power (Model 2: Alpha power = Age + Cue + SOA + Bounce + Sway Velocity + SPPB Score + Pure-tone audiometry + Age*Cue + Age*-Bounce + Age*Velocity + Age*SPPB Score). Prior to the examination of the models, the variables were assessed for violation of the related assumptions; the assessment confirmed that all relevant assumptions were met. To correct for the two models, all regression analyses used an inference criterion for statistical significance of p=.025 corrected from p=.05. . To address the violation of ANOVA assumptions present with percentage data, these grand means were converted into z-scores, following the procedures recommended by Caldwell et al. (2019). Data were analysed and visualised in R Studio (version 4.2.1) using the 'stats' (R Core Team, 2022), 'car' (Fox and Weisberg, 2019), 'performance' (Lüdecke et al., 2021), 'emmeans' (Lenth, 2023) and 'ggplot2' (Wickham, 2016) packages. Post-hoc ANOVAs and correlational analyses were used to analyse the differences and relationships between conditions and age groups. Pure-tone audiometry thresholds were included within each model to control for any age-related differences in hearing ability.

2.5. Deviations from pre-registration

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

3. Results

H1 – Older adults will exhibit increased audiovisual integration compared to younger adults

The difference in the proportion of "Bounce" responses from unisensory conditions compared to multisensory conditions, for each age group, are displayed in Fig. 5.

For Model 1, the outcome was the difference in proportion of "Bounce" responses produced in multisensory compared to unisensory conditions. The model was significant overall [F(11,272) = 2.40, p=.007, adjusted R^2= 0.05. The output from the ANOVA performed on the multiple regression model is displayed in Table 2.

With regards to the individual predictors in the model, there was no

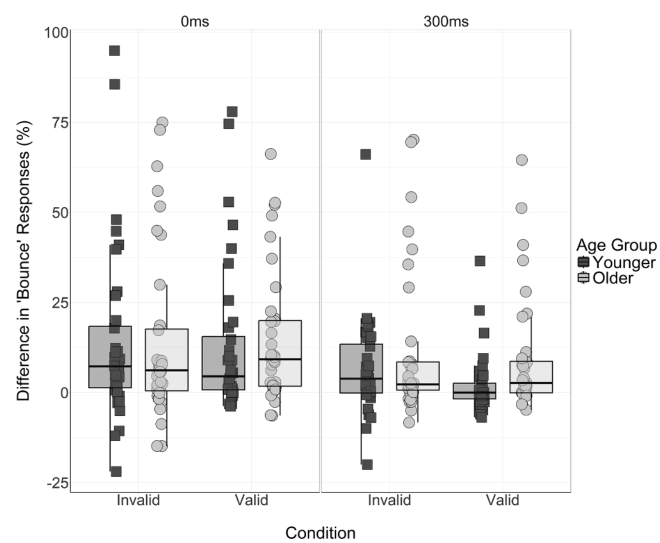

Fig. 5. Difference in the proportion of "Bounce" responses from unisensory conditions compared to multisensory conditions. Black squares represent the data of younger adults, grey circles represent the data of older adults.

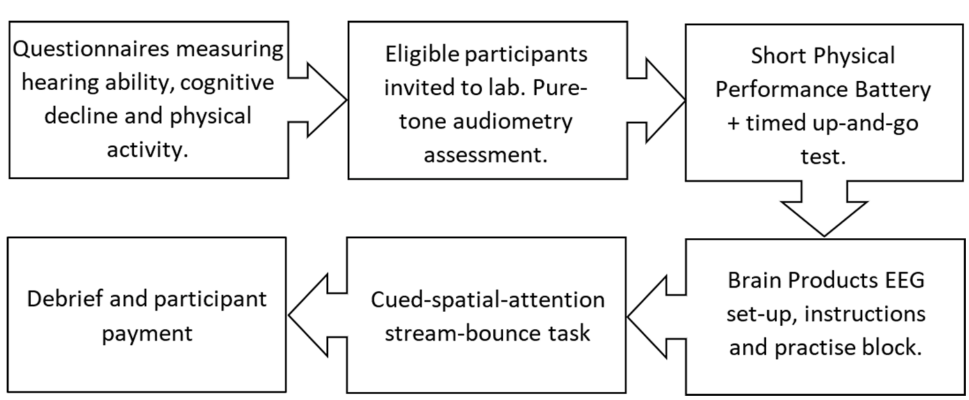

Fig. 4. Flowchart detailing the procedure of the study.

Table 2
Multiple linear regression output detailing the statistical contribution of each predictor and interaction to the outcome of the proportion of "Bounce" responses.

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

Predictors	Df	Sum of squares	Mean square	*F value*	*p*
Age Group	1	2.42	2.42	2.52	.114
Cue	1	0.78	0.78	0.81	.369
SOA	**1**	**8.58**	**8.58**	**8.95**	**.003**
Alpha	1	0.64	0.64	0.67	.413
Sway Velocity	1	0.74	0.74	0.77	.381
SPPB Score	1	0.15	0.15	0.15	.696
PTA	1	4.26	4.26	4.44	.036
Age*Cue	1	0.06	0.06	0.06	.805
Age*Alpha	1	3.33	3.33	3.47	.064
Age*Velocity	1	4.07	4.07	4.25	.040
Age*SPPB Score	1	0.28	0.28	0.29	.590
Residuals	272	260.95	0.96		

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

significant main effect of Age on the proportion of "Bounce" responses [$F(1, 272) = 2.52$, p=.114]. As a result, the data did not provide support for hypothesis one, which predicted that older adults would exhibit increased integration compared to younger adults.

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

The interaction between Age and Cue was not a significant predictor of "Bounce" responses [$F(1, 272) = 0.06$, p=.805]. As a result, the behavioural data do not support hypothesis two, which predicted that older adults will demonstrate weaker attentional control during audiovisual integration compared to younger adults. However, there was a significant main effect of SOA on the proportion of "Bounce" responses [$F(1, 272) = 8.95$, p=.003, ηp^2=0.03]. Overall, a greater increase in "Bounce" responses was produced in 0 ms conditions (M = 14.0 %, SD=21.80) compared to the increase produced in 300 ms conditions (M = 7.33 %, SD=15.50). This indicates that across age groups, increased audiovisual integration occurred within the stream-bounce task when the sound played simultaneously with the circles intersecting, in line with the temporal rule of multisensory integration.

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

Difference in alpha power between unisensory and multisensory conditions, for each age group, are displayed in Fig. 6.

For Model 2, the outcome was the difference in alpha power in multisensory conditions compared to unisensory conditions. The model was significant overall [$F(11, 272) = 2.34$, p=.009, adjusted $R^2 = 0.05$. The output from the ANOVA performed on the multiple regression model is displayed in Table 3.

There was no significant main effect of Age in the model [$F(1, 272)$= 3.17, p=.076]. However, the interaction between Age and Cue significantly predicted difference in alpha power [$F(1, 272) = 5.19$, p=.024, ηp^2=0.02]. To assess differences in alpha power in younger adults during valid versus invalid trials, and in older adults during valid versus invalid trials, ANOVAs were conducted.

For younger adults, there was a significant difference in alpha power between cued locations [$F(1, 142) = 10.22$, p=.002]. In validly-cued conditions, alpha power increased relative to unisensory conditions (M = 2.56, SD=13.1), however in invalidly-cued conditions, alpha power decreased relative to unisensory conditions (M=−3.85, SD=10.9). In contrast, for older adults, there was no significant differences in alpha power changes in validly-cued versus invalidly-cued conditions [$F(1, 142) = 0.001$, p=.969]. This indicates that whilst the alpha power of younger adults was impacted by the attentional manipulation within the task, alpha power of older adults was not. Furthermore, in validly-cued conditions, there was no difference in alpha power change between age groups [$F(1, 142)$=0.08, p=.768]. However, in invalidly-cued conditions, there was a significant difference in alpha power changes between age groups [$F(1, 142)$=12.09, p<.001]; for younger adults, alpha power decreased in multisensory conditions compared to unisensory conditions (M=−3.85, SD=10.9), whereas for older adults, alpha power increased in multisensory compared to unisensory conditions (M = 1.82, SD=8.53). This interaction is displayed in Fig. 7.

Finally, there was a significant main effect of Cue on alpha power [$F(1, 272) = 5.24$, p=.023, ηp^2=0.02]. In validly-cued multisensory conditions, alpha power increased relative to the unisensory conditions (M = 2.23, SD=13.60), whereas in invalidly-cued conditions, alpha power decreased relative to unisensory conditions (M=−1.02, SD=10.10). This indicates that in validly-cued conditions whereby attention can serve to modulate audiovisual integration, alpha power increased to inhibit the task-irrelevant auditory input. Whilst this was not reflected in the behavioural data, it may provide potential support for the role of increased alpha power in inhibitory control.

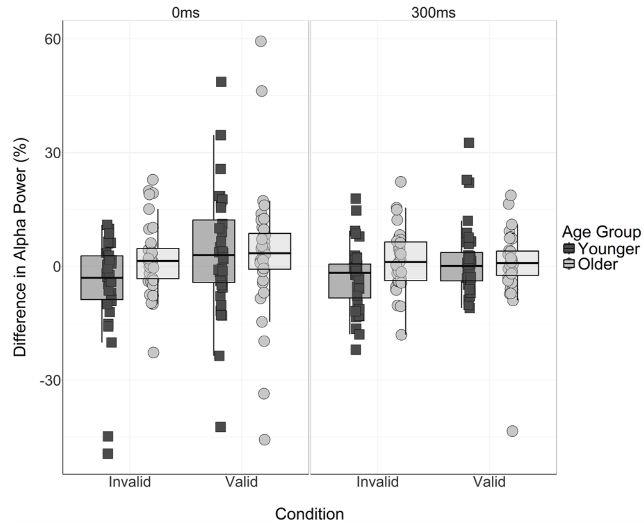

Fig. 6. Difference in alpha power from unisensory conditions compared to multisensory conditions. Black squares represent the data of younger adults, grey circles represent the data of older adults.

Table 3
Multiple linear regression output detailing the statistical contribution of each predictor and interaction to the outcome of alpha power.

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

Predictors	Df	Sum of squares	Mean square	*F value*	*p*
Age Group	1	446	446.13	3.17	.076
Cue	**1**	**737**	**737.26**	**5.24**	**.023**
SOA	1	55	55.11	0.39	.532
Bounce	1	95	95.37	0.68	.411
Sway Velocity	1	527	527.10	3.74	.054
SPPB Score	1	5	5.28	0.04	.847
PTA	1	0	0.27	0.002	.965
Age*Cue	**1**	**731**	**730.62**	**5.19**	**.024**
Age*Bounce	1	294	294.42	2.09	.149
Age*Velocity	1	55	55.05	0.39	.532
Age*SPPB Score	1	669	668.66	4.75	.030
Residuals	272	38,293	140.78		

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

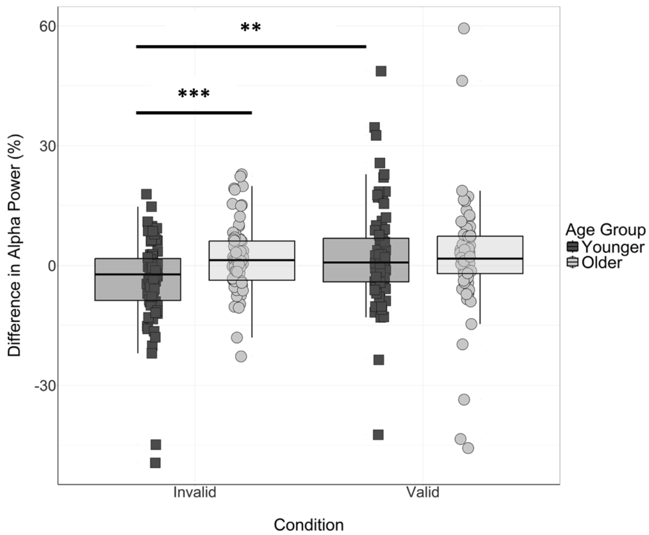

Fig. 7. Significant interaction between Age and Cue predicting difference in alpha power from unisensory to multisensory conditions. Black squares represent the data of younger adults, grey circles represent the data of older adults.

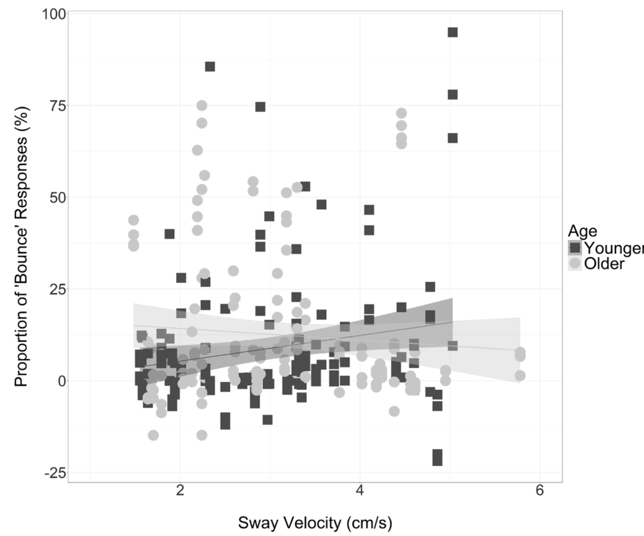

Fig. 8. Significant interaction between the proportion of "Bounce" responses and sway velocity. Black squares represent younger adult data, grey circles represent the older adult data. Younger adults produced a significant positive correlation, whereas older adults did not produce a significant correlation.

H4: Balance will predict audiovisual integration and attentional control

There was no significant main effect of SPPB score on the proportion of "Bounce" responses [Model 1, Table 2; [$F(1, 272) = 0.15$, p=.696. In addition, there was no significant main effect of sway velocity on the proportion of "bounce" responses [$F(1, 272) = 0.77$, p=.381. Furthermore, in Model 2 (Table 3), there was no significant main effect of SPPB score [$F(1, 272)$=0.04, p=.847) or sway velocity [$F(1, 272)$=2.73, p=.054) on change in alpha power. Taken together, the data did not support hypothesis four that weaker functional ability or balance ability would predict audiovisual integration (as indexed by "Bounce" responses) and attentional control (as indexed by alpha power) within the stream-bounce task.

Our criterion for significance was set at p=.025 for the current study; however, the interaction between Age and Sway Velocity was a significant predictor of "Bounce" responses at the p=.05 level [$F(1, 272) = 4.25$, p=.040, ηp^2=0.02]. Exploratory correlations revealed that for younger adults, there was a significant positive correlation between the proportion of "Bounce" responses and sway velocity [$r(142) = 0.19$, p=.021). In contrast, for older adults, there was no significant correlation between the proportion of "Bounce" responses and sway velocity [$r(138) = -0.09$, p=.316]. This indicates that in younger adults, weaker modulation of audiovisual integration (i.e. increased "Bounce" responses") was associated with weaker balance maintenance (greater sway velocity). This significant interaction is displayed in Fig. 8.

Participants SPPB scores and sway velocities are displayed in Figs. 9 and 10.

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

4. Discussion

The aims of this study were to 1) investigate the role of parieto-occipital alpha power in age-related changes in audiovisual integration, and 2) investigate the association between audiovisual integration

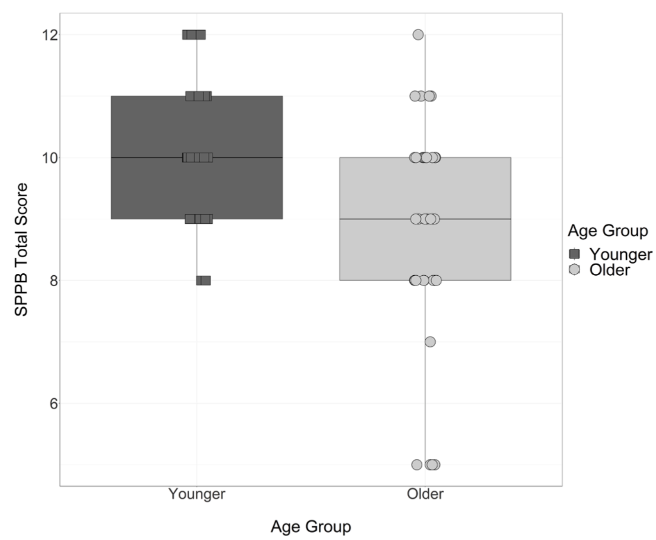

Fig. 9. Short Physical Performance Battery scores for all participants. Black squares and boxplot represent data of younger adults, grey circles and boxplot represent the data of older adults. Each boxplot displays the median, the lower and upper quartile for each condition.

and balance ability. Whilst behavioural results from the stream-bounce task do not provide support for the theory that older adults exhibit increased audiovisual integration compared to younger adults, important conclusions can be made with regards to the role of oscillatory alpha power in attentional control during multisensory integration, and how this may change with healthy ageing. Furthermore, findings may suggest that attentional resources may be deployed differently for younger and older adults during balance maintenance.

4.1. Older adults did not display weaker attentional control during audiovisual integration compared to younger adults

The finding that younger and older adults produced a similar increase in "Bounce" responses in multisensory compared to unisensory conditions is in contrast to our hypothesis. The results of the current study may also call into question the universality of the inhibitory deficit

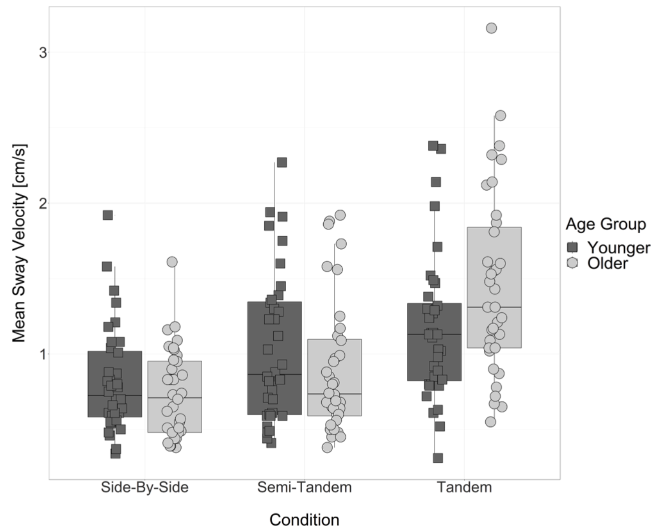

Fig. 10. Mean sway velocity recorded for each participant in the side-by-side, semi-tandem and tandem balance positions in the Short Physical Performance Battery. Black squares and boxplots represent data of younger adults, grey circles and boxplots represent the data of older adults. Each boxplot displays the median, the lower and upper quartile for each condition.

Table 4
Mean scores on the ABC and RAPA self-report questionnaires on balance confidence and physical activity, for both younger and older adults. Standard deviations displayed in parentheses.

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

hypothesis (Hasher and Zacks, 1988), whereby older adults have been posited to have weaker top-down inhibition of task-irrelevant information compared to younger adults. The older adult sample recruited in this experiment displayed strong attentional control, being as proficient as younger adults inhibiting the task-irrelevant tone.

At this point, it is important to acknowledge that research into age-related changes in attentional control during multisensory integration has produced highly mixed findings (Jones and Noppeney, 2021). Whilst such substantial variations have previously been attributed to issues like task-dependency and discourse as to how veridical inhibiton can be measured (Rey-Mermet and Gade, 2018), we suggest that individual differences across older adult samples can also impact whether age-related changes in multisensory integration are detected. Indeed, heterogenous ageing trajectories mean that whilst some older adults may experience weaker inhibition as a function of healthy ageing, others may be more robust to such declines and find alternative strategies to preserve cognitive function (Daskalopoulou et al., 2019; Oosterhuis et al., 2023). Specifically, external factors such as years of education, amount of socialisation, and levels of physical activity can contribute to "cognitive reserve" (Stern et al., 2020; Oosterhuis et al., 2023). Older adults with higher levels of cognitive reserve can strengthen existing brain networks to facilitate the use of alternative cognitive strategies (Stern et al., 2020; Oosterhuis et al., 2023); this cognitive flexibility can potentially preserve performance – to the extent to which, in the current context, older adults with higher levels of cognitive reserve are similarly efficient as younger adults at inhibiting the task-irrelevant tone in the stream-bounce task.

Whilst no formal measures of cognitive reserve were recorded in this study, demographic data such as ABC and RAPA scores reflect the high physical ability of the current older adult sample, which indeed contributes to high cognitive reserve. In sum, varying degrees of cognitive reserve across different older adult samples may lead to mixed findings across the literature investigating multisensory integration and ageing. It is important that future studies implement measures of cognitive reserve to a) identify the cognitive flexibility/resilience of their older adult sample, b) assess whether the older adult sample recruited is diverse enough to be representative of the cognitive abilities of the wider older adult population, and c) potentially implement participants' cognitive reserve scores as covariates in statistical analyses, to account for the impact of individual differences in cognitive functioning on the behavioural or neural data observed. At minimum, proxies of cognitive reserve could be measured using individual factors known to contribute to it, such as years of education or levels of socialisation (Oosterhuis et al., 2023). However, a more comprehensive account would be achieved through implementing a cognitive reserve measure which evaluates multiple key subscales together, such as the Cognitive Reserve Index questionnaire (CRIq; Nucci et al., 2012). The CRIq assesses each participant's educational experiences, working activities and leisure activities across the lifespan, calculating a composite cognitive reserve score. Not only does this tool provide a detailed account of the scope and frequency of cognitive reserve-building activities an individual has carried out across their lifespan, but the standardised scoring also allows for clearer comparisons of cognitive reserve levels between individuals.

4.2. Stimulus-onset asynchrony significantly predicted audiovisual integration in the stream-bounce task

The significant main effect of SOA in Model 1 provides an important reflection of the "temporal rule" of multisensory integration – bimodal inputs which are presented closely together in time are more likely to be perceived as occurring from the same event, and bound together into a single perceptual entity (Meredith and Stein, 1985; Bedard and Barnett-Cowan, 2016). Our findings indicate that 0 ms trials produced a greater increase in "Bounce" responses from unisensory conditions compared to the increase produced in 300 ms conditions; when the task-irrelevant sound played simultaneously with the circles intersecting, illusory "Bounce" responses increased across all age groups, to a greater extent than when the sound was played after the intersection. The temporal interval over which bimodal stimuli can be presented and subsequently integrated is known as the temporal binding window (TBW; Diederich and Colonius, 2015; Powers et al., 2009; Pepper et al., 2023). It is well-established in previous research that as the temporal interval (i.e. SOA) between visual and auditory increases, the likelihood of multisensory integration decreases (Stevenson et al., 2012 van Wassenhove et al., 2007; Vatakis and Spence, 2006). It follows that individuals with greater temporal precision (i.e. narrower TBWs) are better able to identify bimodal inputs which are asynchronous and therefore should not be bound together.

Despite the utility of the stream-bounce illusion in unpicking how the temporal rule of multisensory integration can produce illusory percepts, the task has been previously criticised as too indirect a method for measuring how temporal precision during multisensory processing may change with healthy ageing (Sekuler et al., 1997; Basharat et al., 2019). Future research may instead choose to implement more low-level methods of measuring the TBW, such as simultaneity judgements or temporal order judgement tasks (Basharat et al., 2019; Bedard and Barnett-Cowan, 2016), which may be more sensitive indications of temporal precision within multisensory integration. We would argue, however, that the use of dynamic visual stimuli is useful for studying the impact of age-related changes in audiovisual integration on fall risk in particular, due to the importance of e.g. optic flow mechanisms in guiding safe locomotion and maintaining balance (Raffi and Piras, 2019; Peterka, 1995).

It is also interesting to consider how the TBW in multisensory integration may be reflected neurally. Indeed, whilst alpha activity has been investigated from a top-down perspective in this study, there is also evidence that individual alpha frequency (IAF) is associated with bottom-up elements of multisensory processing, such as the width of the TBW (Keil and Senkowski, 2018). The lower the IAF, the wider the TBW and the greater the likelihood of erroneous integration when visual and auditory stimuli are temporally incongruent (Keil and Senkowski, 2018; Pepper and Nuttall, 2023). Despite the importance of this neural correlate in furthering our understanding of temporal processing during multisensory integration, limited research has been conducted investigating how the relationship between IAF and the TBW may change with healthy ageing. This would be a compelling area for future research to understand how neural oscillations within the alpha-band frequency can govern both bottom-up and top-down processes during multisensory integration, and how this may be affected by increasing age.

4.3. Oscillatory alpha power did not predict audiovisual integration

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

4.4. Interactions between age and cue significantly predicted alpha power

Results from Model 2 indicated that an interaction between Age and Cue significantly predicted changes in alpha power from unisensory to multisensory conditions. Younger adults displayed an increase in alpha power in validly-cued multisensory conditions, and a decrease in alpha power in invalidly-cued multisensory condition. Crucially, older adults did not display differences in alpha power regardless of whether the cue was valid or invalid. This age group difference was not reflected in behavioural data, which may indicate that different neural mechanisms between age groups may subserve similar behavioural performance. That is, whilst alpha activity is a key neural correlate for attention and inhibition in younger adults, there may be wider brain networks or alternative frequency bands involved in maintaining behavioural performance in older adults.

Indeed, in the context of speech perception, alpha oscillators in parietal regions may be less effective in older adults compared to younger adults (Herrmann et al., 2023). Wöstmann et al. (2015) found that during a complex speech-in-noise task, older adults displayed reduced parietal alpha power compared to younger adults. From this, Herrmann et al. (2023) posited that whilst parietal alpha may dominate for younger adults during inhibition, alpha activity in temporal/auditory brain regions may dominate in older adults. That is, during speech perception, if parietal alpha oscillators are less involved in listening for older adults, perhaps a compensatory strategy is employed that leads to an increased engagement of alpha oscillators in auditory cortex (Herrmann et al., 2023). Whilst speech perception is considerably more complex than the stream-bounce task, future studies investigating age-related changes in alpha power during multisensory processing should explore the role of different brain regions in attentional control in younger versus older adults.

Accordingly, future research should focus on investigating more complex audiovisual stimuli that participants encounter in real-world environments (e.g. speech). Indeed, whilst the stream-bounce illusion may be effective at uncovering the importance of temporal precision in multisensory integration (as discussed), the cued-spatial-attention version of the task as implemented in the current study may be insufficiently sensitive to detect complex age-related changes in attentional control during audiovisual integration. Implementing more cognitively demanding tasks, such as audiovisual speech perception in noisy listening environments, or under dual-task conditions, would allow researchers to arrive at more ecologically valid conclusions regarding age-related changes in the interplay between attentional control and temporal processing.

4.5. An interaction between age and sway velocity may predict audiovisual integration

The interaction between sway velocity and age group significantly predicted the proportion of “Bounce” responses at the p=.05 level, though inference criteria for our study was defined as p=.025. This may provide tentative support for the differential role of audiovisual integration in balance maintenance for younger and older adults, with a larger sample potentially required to power that specific interaction. .

The interaction found in the current study revealed that older adults did not show a significant correlation between audiovisual integration in the stream-bounce task and sway velocity, whilst younger adults did. For younger adults, a greater proportion of “Bounce” responses (i.e. increased audiovisual integration) was associated with greater sway velocity (i.e. weaker balance ability). This may indicate that whilst efficient multisensory integration and strong attentional control is an important factor for younger adults’ balance ability, it may not be as central to balance maintenance for older adults, who could rely on alternative strategies for balance in the face of any age-related declines in sensory or attentional processes.

Indeed, previous research suggests that age-related declines in sensorimotor tracts within posture control loops result in the increased activation of cortical brain regions for balance maintenance in older adults (Pepper and Nuttall, 2023; Kahya et al., 2019; Malcolm et al., 2021; Ozdemir et al., 2018). For example, Ozdemir et al. (2018) found increased gamma activity in central, frontal and central-parietal areas of older adults when sensory information is compromised; these increases in gamma activity have previously been attributed to sustained attention (Slobounov et al., 2009). Ozdemir et al. (2018) postulated that older adults may allocate increased attentional resources to postural control than younger adults, requiring the recruitment of wider brain regions involved in motor control and executive function to maintain balance.

This is in line with the scaffolding theory of cognitive ageing (Reuter-Lorenz and Park, 2014; Oosterhuis et al., 2023), which is associated with cognitive reserve theories discussed earlier. That is, the increased recruitment and activation of frontal and motor brain regions may be a compensatory strategy for older adults to maintain balance despite neural degeneration of balance centres (Oosterhuis et al., 2023; Kahya et al., 2019; Park and Reuter-Lorenz, 2009; Montero-Odasso et al., 2017). Whilst in the current study, age-related differences in balance did not predict alpha activity in Model 2, tentative conclusions can be made from Model 1 with regards to the differential importance of audiovisual integration for balance in each age group – it may be that the increased engagement of cortical motor regions is the predominant factor in balance maintenance for older adults, as opposed to any age-related changes in audiovisual processing.

It is important that future research focusses on uncovering the age-related changes in the cortical mechanisms required for balance maintenance, as at the moment, the evidence into such changes appears to be limited (Malcolm et al., 2021; Ozdemir et al., 2018).

4.6. Measuring balance and cognition in high-functioning older adults

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

Whilst the SPPB and sway velocity measures serve as valuable objective measures of functional ability and balance, the ABC and RAPA provide interesting insights into the strong physical abilities of our older adult sample. Despite being subjective measures (and therefore may be more prone to individual bias compared to the SPPB, for example), both the ABC and the RAPA are used in clinical practice to indicate participants' own perception of their physical ability. The ABC has been found to have good internal consistency and test-retest reliability (Powell and Myers, 1995), whilst the RAPA is reported to have better specificity and predictive value compared to alternative physical activity questionnaires (Topolski et al., 2006). As a result, the lack of significant difference between younger and older adults on both questionnaires can be confidently interpreted as the older adults in our sample possessing higher balance confidence and higher levels of physical activity compared to older adults who may be more frail. On the other hand we acknowledge that the use of subjective measures of cognitive impairment, such as the IQCODE implemented as a pre-screening measure, may be prone to bias and is designed to be completed by a third party (e.g. a caregiver). Alternative cognitive screening questionnaires, such as the Montreal Cognitive Assessment or the Mini Mental State Examination, are recommended as more robust, quantitative measures to confirm that the sample of older adults recruited in future studies are not experiencing mild cognitive impairment.

4.7. Practical applications and future considerations

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

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

Furthermore, a potential limitation of this study is that the age-related behavioural and neural changes in attentional control during audiovisual integration during the stream-bounce task were measured separately to the participants' balance abilities. This may mean that whilst association between attentional control and balance can be inferred, conclusions with regards to the impact of age-related changes in attentional control on balance, based on our task, are less direct. As such, future research should focus on measuring attentional control during multisensory integration whilst balance is being manipulated – this kind of dual-task paradigm would not only provide useful insights into how attention may be divided between two concurrent multisensory tasks, but is also likely to uncover how such attentional allocations may change as a function of healthy ageing.

5. Conclusions

To conclude, the weaker top-down modulation of multisensory integration in older adults can have serious implications for their perception of and navigation through their dynamic environment, however as yet, research into such age-related changes has produced mixed findings. Whilst behavioural data in this study did not provide support for the theory that older adults show weaker inhibition of task-irrelevant information compared to younger adults, neural data revealed age-related changes in alpha activity during the attentional modulation of multisensory integration. Tentative conclusions can also be made in that younger and older adults may employ differing cognitive and neural mechanisms for balance maintenance. To determine the underlying neural correlates of age-related changes in the top-down and bottom-up mechanisms of multisensory integration, and how these affect fall risk, it may be important to analyse neural activity from multiple frequency bands and brain regions, to understand how different oscillations and neural networks may coordinate to support multisensory perception and action. Future research must also investigate the possibility of younger and older adults using different strategies in facilitating the processing of task-relevant information and inhibiting task-irrelevant information; each age group may rely upon different brain areas and different mechanisms to support multisensory integration, compensating for age-related neurodegeneration. Developing a detailed understanding of the age-related changes in multisensory integration, and how this may influence fall risk, could provide important direction for the design of cognitive treatments to sharpen the perception of older adults and improve their allocation of attentional resources during balance maintenance.

Data and code availability statement

All code and data will be made available via the Open Science Framework (OSF) following publication. The OSF project can be found here: https://osf.io/hv29j/

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CRediT authorship contribution statement

Jessica L. Pepper: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Bo Yao:** Writing – review & editing, Visualization, Software, Formal analysis, Data curation. **Jason J. Braithwaite:** Writing – review & editing, Supervision. **Theodoros M. Bampouras:** Writing – review & editing, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Helen E. Nuttall:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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