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Older Adults with Clinically Normal Sensory and Cognitive Abilities Perceive Audiovisual Simultaneity and Temporal Order Differently than Younger Adults

Stephanie Yung [1,2], **M. Kathleen Pichora-Fuller** [2], **Dirk B. Walther** [2], **Raheleh Saryazdi** [1,3] **and Jennifer L. Campos** [1,2,4,*]

[1] KITE — Toronto Rehabilitation Institute, University Health Network, Toronto, ON, Canada
[2] Department of Psychology, University of Toronto, Toronto, ON, Canada
[3] Department of Psychology, Trent University Durham, Oshawa, ON, Canada
[4] Rehabilitation Sciences Institute, University of Toronto, Toronto, ON, Canada
[*]Corresponding author; e-mail: Jennifer.Campos@uhn.ca
ORCID iDs: Kathleen Pichora-Fuller: 0000-0002-7812-2863; Walther: 0000-0001-8585-9858; Saryazdi: 0000-0002-7871-2388; Campos: 0000-0002-7054-3946

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Abstract

It is well established that individual sensory and cognitive abilities often decline with older age; however, previous studies examining whether *multisensory* processes and multisensory integration also change with older age have been inconsistent. One possible reason for these inconsistencies may be due to differences across studies in how sensory and cognitive abilities have been characterized and controlled for in older adult participant groups. The current study examined whether multisensory (audiovisual) synchrony perception is different in younger and older adults using the audiovisual simultaneity judgement (SJ) and temporal order judgement (TOJ) tasks and explored whether performance on these audiovisual tasks was associated with unisensory (hearing, vision) and cognitive (global cognition and executive functioning) abilities within clinically normal limits. Healthy younger and older adults completed audiovisual SJ and TOJ tasks. Auditory-only and visual-only SJ tasks were also completed independently to assess temporal processing in hearing and vision. Older adults completed standardized assessments of hearing, vision, and cognition. Results showed that, compared to younger adults, older adults had wider temporal binding windows in the audiovisual SJ and TOJ tasks and larger points of subjective simultaneity in the TOJ task. No significant associations were found among the unisensory (standard baseline and unisensory SJ), cognitive, or audiovisual (SJ, TOJ) measures. These findings suggest that audiovisual integrative processes change with older age, even within clinically normal sensory and cognitive abilities.

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multisensory processes, audiovisual synchrony, simultaneity judgement, temporal order judgement, ageing, individual differences, sensory function

1. Introduction

Changes in hearing and vision are common in older adults (Campos *et al.*, in press; Cavazzana *et al.*, 2018; Schneider *et al.*, 2011), and auditory and visual integration processes may also change with older age (de Dieuleveult *et al.*, 2017; Mozolic *et al.*, 2012; Wallace *et al.*, 2020). Effective audiovisual integration is important for many everyday abilities and functional behaviours such as understanding speech, as well as complex mobility-related tasks such as driving (Ramkhalawansingh *et al.*, 2016, 2018; Taitelbaum-Swead and Fostick, 2016). In some studies, older adults have been shown to experience greater multisensory (relative to unisensory) benefits than younger adults. For instance, while both older and younger adults show faster response times and more precise estimates for multisensory events than for unisensory events, the magnitude of multisensory benefits is often larger in older adults than in younger adults (Basharat *et al.*, 2019; Diederich *et al.*, 2008; Irwin and DiBlasi, 2017; Laurienti *et al.*, 2006; Peiffer *et al.*, 2007; Puschmann *et al.*, 2019; Werkhoven *et al.*, 2014). However, explanations of when and why 'heightened' multisensory integration occurs with ageing have been inconsistent across the literature. This may be due to factors such as differences in the nature of the audiovisual tasks (Bak *et al.*, 2021; Basharat *et al.*, 2018; Love *et al.*, 2018; Schormans *et al.*, 2017; Scurry *et al.*, 2019; van Eijk *et al.*, 2008; Weiß and Scharlau, 2011), the characteristics of the sensory stimuli used across studies (Boenke *et al.*, 2009; Chan *et al.*, 2014a, b, 2016; Fister *et al.*, 2016; Fujisaki *et al.*, 2004; Stevenson and Wallace, 2013), or most relevant to the current study, individual differences in participants' sensory and cognitive abilities (Brooks *et al.*, 2018; Donohue *et al.*, 2015; Hernández *et al.*, 2019; Zhou *et al.*, 2020).

1.1. Measures of Audiovisual Temporal Processing

The temporal factors influencing multisensory processing have received much attention in the audiovisual integration literature. The brain's ability to perceive the relative timing of an auditory and visual input is important for determining whether these sensory inputs should be integrated (i.e., when inputs are jointly related to a single object or event), or segregated (i.e., when they are nonrelated sensory events). Auditory and visual inputs that occur more closely in time are more likely to be integrated than those with larger temporal separations. When temporal offsets between auditory and visual inputs reach an upper limit, these inputs are more likely to be perceived as separate events.

The range of temporal offsets for which multisensory inputs are more likely to be integrated is commonly referred to as the temporal binding window (TBW) (Diederich and Colonius, 2015; Spence and Parise, 2010). The TBW has been assessed, for example, using the audiovisual simultaneity judgement (SJ) task and the temporal order judgement (TOJ) task (Bedard and Barnett-Cowan, 2016; Love *et al.*, 2018; Vroomen and Keetels, 2010). In both tasks, an auditory stimulus and a visual stimulus are presented with a variable time delay, referred to as the stimulus onset asynchrony (SOA). In the SJ task, participants judge whether the auditory and visual stimuli occurred simultaneously (e.g., at 'same' or 'different' times), while in the TOJ task, participants judge which of two stimuli were presented first ('visual-leading' or 'auditory-leading'). By fitting psychometric functions to the proportion of 'same' or 'visual-leading' responses on the audiovisual SJ and the TOJ tasks respectively, performance measures such as the TBW and the point of subjective simultaneity (PSS) can be obtained. The PSS is understood as the smallest SOA at which participants perceive the sensory inputs as occurring at the same time (Noel *et al.*, 2015; Weiß and Scharlau, 2011). Narrower TBWs and smaller PSSs tend to indicate better temporal precision and accuracy, respectively.

1.2. Differences Between Audiovisual Simultaneity and Temporal Order Judgements in Younger and Older Adults

Studies have demonstrated few associations between audiovisual SJ and TOJ performance measures, suggesting that audiovisual SJs and TOJs may reflect different perceptual processes (Basharat *et al.*, 2018; Bedard and Barnett-Cowan, 2016; Harrar *et al.*, 2017; Linares and Holcombe, 2014; Love *et al.*, 2018; Scurry *et al.*, 2019; Vroomen and Keetels, 2010; Weiß and Scharlau, 2011). Some studies examining age-related differences in audiovisual SJs have shown that older adults have wider TBWs and larger PSSs than younger adults (Chan *et al.*, 2014a,b; Noel *et al.*, 2016), indicating that the precision and accuracy of perceived synchrony for audiovisual events may change with older age. Some studies that examined age-related differences in audiovisual TOJs have shown that older adults respond less accurately and have a wider TBW than younger adults (De Boer-Schellekens and Vroomen, 2014; Setti *et al.*, 2011), indicating that temporal sensitivity for audiovisual events may also decline with older age. However, the findings are mixed, with other studies demonstrating no age-related effects on SJ and/or TOJ performance measures (e.g., Basharat *et al.*, 2018; Bedard and Barnett-Cowan, 2016; Fiacconi *et al.*, 2013). To our knowledge, there are only a few studies that have compared performance of healthy younger and older adults on measures of both audiovisual SJs and TOJs within the same sample of participants (Basharat *et al.*, 2018, 2019; Bedard and Barnett-Cowan, 2016), with inconsistent age-related effects across these studies. Specifically, Bedard and Barnett-Cowan (2016) reported a wider window of integration in the audiovisual TOJ task in older than younger adults, with no age-related differences for the audiovisual SJ task. Meanwhile, Basharat *et al.* (2018, 2019) did not find any significant behavioral differences (TBW, PSS) between younger and older adults for either the audiovisual SJ or TOJ tasks. Overall, these inconsistences in the literature may be related to differences across studies with respect to the unisensory and cognitive abilities of the sample of participants. Indeed, interindividual differences in unisensory functioning have been speculated to modulate performance in audiovisual SJ and TOJ tasks (Basharat *et al.*, 2018; Brooks *et al.*, 2018; Diederich *et al.*, 2008; Jones and Noppeney, 2021; Mozolic *et al.*, 2012). It is difficult to determine from the current literature whether reported audiovisual SJ and TOJ performance may be influenced by unaccounted for, or unreported, differences in the sensory or cognitive abilities of the participants.

1.3. Age-Related Changes in Vision, Hearing, and Cognition Influencing Audiovisual Processes

Overall, within the literature on age-related changes to multisensory integration, screening for sensory impairments/abilities does not always occur, with only just over half of these studies screening for vision (51%) and hearing (64%) impairment (Basharat *et al.*, 2022), fewer than half using objective measures, and a lack of consistency in criteria for defining ‘normal’. Some previous studies of audiovisual integration have attempted to partially control for individual differences in sensory abilities by pre-screening for sensory impairments using self-report questions (Basharat *et al.*, 2018, 2019; Bedard and Barnett-Cowan, 2016; Chan *et al.*, 2018; De Boer-Schellekens and Vroomen, 2014; Scurry *et al.*, 2019; Stevenson *et al.*, 2018). Some studies have included measures of unisensory temporal performance using visual-only and/or auditory-only TOJ tasks (Busey *et al.*, 2010; De Boer-Schellekens and Vroomen, 2014; Stevenson *et al.*, 2018). Few studies have included one or more objective tests of sensory ability using standardized behavioural tests such as audiometric tests and eye charts (Chan *et al.*, 2014a,b, 2017; Fiacconi *et al.*, 2013; Noel *et al.*, 2016), and/or included objective screening measures of global cognitive functioning such as the Montreal Cognitive Assessment (Nasreddine *et al.*, 2005) or the Mini Mental State Exam (Basharat, 2019; Fiacconi *et al.*, 2013; Folstein *et al.*, 1975; Setti *et al.*, 2011). As such, it is unclear whether age-related differences in SJ and/or TOJ performance persist when impairments in unisensory and/or cognitive functioning have been accounted for.

Age-related declines in visual acuity and hearing detection thresholds are common (Mick *et al.*, 2021; World Health Organization, 2019, 2021). Examples of age-related sensory declines that could affect audiovisual abilities include decreased visual acuity and reduced contrast sensitivity (Owsley, 2011), higher pure-tone audiometric thresholds, and poorer auditory signal-in-noise detection thresholds (Dubno *et al.*, 2013; Humes, 2019; Rosemann *et al.*, 2020). While it is well known that the prevalence of clinically significant impairments in hearing and vision thresholds increase with older age, many older adults also experience sub-clinical, age-related changes in hearing and vision related to suprathreshold processing of sensory information (Fitzgibbons and Gordon-Salant, 1996; Owsley, 2011; Schneider *et al.*, 2002). Importantly, normal sensory acuity as measured through standardized behavioural tests does not preclude declines in suprathreshold unisensory abilities such as temporal processing abilities. These age-related sensory changes may influence how auditory and visual inputs are integrated and perceived as a unified, coherent percept. Common tests of unisensory temporal processing measure the precision with which one can detect the onset and offset of single-modality sensory events (e.g., two visual flashes or two auditory tones). In vision, temporal processing has been measured, for example, with flicker-fusion tasks (Eisen-Enosh *et al.*, 2017). Results of these tests have shown that even older adults with normal Snellen visual acuity and normal ocular health as determined by direct and indirect ophthalmoscopy are less sensitive at perceiving gaps in rapidly presented sequential flashes than younger adults (Kim and Mayer, 1994). In hearing, common measures of temporal processing include auditory gap detection or discrimination tasks (Humes and Dubno, 2010; Humes *et al.*, 2012; Phillips, 1995; Schneider *et al.*, 1994; Shinn and Musiek, 2003). Results of these tests have shown that older adults are less precise than younger adults at detecting gaps in speech and nonspeech sounds, even when they have clinically normal or near-normal hearing in both ears as determined by pure-tone audiometry (Pichora-Fuller *et al.*, 2006). Older adults also exhibit larger declines in visual temporal processing than auditory temporal processing, possibly because the visual system is more spatially tuned compared to the auditory system, which is more temporally tuned (Burr *et al.*, 2009; De Boer-Schellekens and Vroomen, 2014; Gori *et al.*, 2012; Humes *et al.*, 2013; Saija *et al.*, 2019). Therefore, in addition to standardized clinical tests of sensory functioning, it is also important to consider evaluations of suprathreshold unisensory processing, for example, through the use of audio and visual temporal processing measures (e.g. unisensory TOJ and SJ tasks).

Few studies have examined how age-related differences in unisensory temporal processing are associated with audiovisual temporal processing. In a sample of older adults from the general Irish population ($n = 2920$), Hirst and colleagues (2019) examined the influences of visual acuity and contrast sensitivity, as well as self-reported hearing and visual abilities (based on a scale from 1 to 5, from poor to excellent), on susceptibility to the sound-induced flash illusion (SIFI); the perception of two flashes when two sounds are presented alongside one flash. Their results showed that self-reported hearing ability and objectively measured visual acuity mediated susceptibility to the SIFI in older adults when controlling for age.

Several previous studies have evaluated the extent to which auditory-only and visual-only TOJ task performance predicts audiovisual task performance (De Boer-Schellekens and Vroomen, 2014; Stevenson *et al.*, 2018). For instance, Stevenson *et al.* (2018) demonstrated that, although older adults required more time to correctly detect the presentation order of sensory stimuli in a visual-only TOJ and an auditory-only TOJ compared to younger adults, unisensory TOJ performance did not predict audiovisual SJ performance. However, given that audiovisual SJ and TOJ tasks may characterize different perceptual processes (Basharat *et al.*, 2018; Love *et al.*, 2013a, 2018; Scurry *et al.*, 2019), it remains unclear whether unisensory temporal processing may uniquely influence audiovisual SJs and TOJs in older and younger adults.

Age-related vision, hearing, and dual-sensory impairments are also associated with an increased risk of cognitive decline (Albers *et al.*, 2015; Baltes and Lindenberger, 1997; Curhan *et al.*, 2019; Davidson and Guthrie, 2019; Lindenberger and Baltes, 1994; Livingston *et al.*, 2017, 2020). For example, lower visual acuity, higher pure-tone audiometric thresholds, and worse performance on vision and hearing temporal processing tasks (e.g., auditory gap detection task) have been associated with lower global cognitive scores as measured by the MoCA and the MMSE (Busey *et al.*, 2010; Folstein *et al.*, 1975; Humes *et al.*, 2013; Humes and Young, 2016). It is therefore reasonable to speculate that changes in audiovisual integration may be associated with changes in cognitive abilities. There is some evidence that older adults with mild cognitive impairment (MCI) are more susceptible to the SIFI compared to cognitively healthy controls (Chan *et al.*, 2015) and that older adults with lower scores on the MoCA are more susceptible to the SIFI compared to older adults with higher MoCA scores (Hernández *et al.*, 2019). Several previous audiovisual integration studies screened participants for cognitive impairments using the MoCA or MMSE as an eligibility criterion (Fiacconi *et al.*, 2013; Setti *et al.*, 2011), but to our knowledge, few studies have yet examined associations among particular cognitive abilities (e.g., executive functioning), unisensory abilities, and audiovisual temporal processing (i.e., SJ and TOJ tasks) in older adults who have no clinically significant cognitive impairment.

1.4. Current Study

Overall, evidence of whether there are age-related differences in audiovisual processes generally, and synchrony perception specifically, is inconsistent, even between studies that compare the audiovisual SJ and TOJ tasks within the same study in younger and older adults. It is not clear whether some of these inconsistencies may be due to the individual sensory and cognitive abilities of the participants in the samples. Therefore, this study aimed to (1) examine age-related differences in audiovisual SJs and TOJs in healthy younger and older adults with verified clinically normal sensory and cognitive functioning, and (2) examine whether such differences are associated with hearing, vision, and cognitive abilities assessed using multiple tests to characterize individual differences that might affect SJs and TOJs.

2. Methods

2.1. Participants

Twenty-six younger adults between the ages of 18 and 29 years ($M_{\mathrm{Age}} = 24.3$ years, $\mathrm{SD}_{\mathrm{Age}} = 3.65$; 15 females) and 28 older adults over the age of 65 years ($M_{\mathrm{Age}} = 71.6$ years, $\mathrm{SD}_{\mathrm{Age}} = 5.03$ years; 17 females) were recruited from the community. Over the telephone, participants were pre-screened to determine eligibility based on self-reported normal or corrected-to-normal vision, self-reported normal hearing (i.e., no clinical diagnosis of hearing loss), no eye diseases such as glaucoma or cataracts, no history of serious medical conditions in the past 10 years (e.g., stroke, head injuries, epilepsy and/or seizures), and no current diagnoses of psychiatric illnesses. Participants were not eligible for the study if they reported diagnoses of MCI and dementia, or subjective cognitive decline (concerns about their memory, thinking, or attention that are worrisome). Participants who met all pre-screening eligibility criteria were invited to the lab to complete the study. The study consisted of two study sessions: (1) a formal baseline assessment session to evaluate sensory, motor, cognitive functioning and (2) an experimental session to evaluate visual-auditory temporal processing (SJ and TOJ tasks). Older adult participants completed both sessions, while younger adult participants only completed the experimental session and a sub-set of the tasks in the baseline assessment session (see Table 1). In the baseline assessment session, older adults completed behavioural tests of vision, hearing, and cognition. Some measures from the baseline assessment session were used as additional eligibility criteria for inclusion in the experimental session. Specifically, older adult participants were only included if they showed a better ear pure-tone air-conduction threshold average (BPTA) for frequencies of 0.5, 1, 2, and 3 kHz of $\leqslant$25 dB HL, with no significant asymmetry (no interaural difference $>$15 dB HL at more than two adjacent octave frequencies; Schneider *et al.*, 1994). Furthermore, older participants were included only if they scored at least 26 out of 30 on the MoCA, the recommended cut-off for normal cognition (Nasreddine *et al.*, 2005). In total, three older adult participants were excluded from the analyses due to measurable hearing loss based on the aforementioned BPTA criteria. Three additional younger adults were excluded due to technical issues.

Table 1.
Participant demographics, sensory and cognitive test characteristics

	Younger adults($n = 23$)			Older adults ($n = 25$)			p-values
	M	SD	Range	*M*	SD	Range	
Demographics							
Age (years)	23.7	3.05	18–29	71.6	5.22	65–86	<0.01
Sex (females:males)	14:9			15:10			
Vision							
ETDRS	0.08	0.15	−0.12–0.40	0.12	0.13	−0.06–0.45	0.42
Pelli–Robson[2]				1.62	0.17	1.20–1.95	
Hearing							
BPTA[3]				10.8	6.33	0–22.50	
Dichotic Digits Test				95.4	4.26	84–100	
SSQ[4]				7.90	2.08	4.54–9.94	
Cognition							
MoCA[5]				27.6	1.38	26–30	
Stroop [6]	34.1	13.8	8.59–54	35.5	15.3	0–63	0.76
Trail-Making Test[7]				9.84	19.4	−1.45–62.64	

Significance level of $p < 0.05$. Three younger adults did not complete the Early Treatment Diabetic Retinopathy Study (ETDRS) and the Stroop task.

[1] ETDRS score for corrected vision in both eyes in logMAR units.

[2] Pelli–Robson score for contrast sensitivity in both eyes in logCS unitS.

[3] BPTA = Better-ear pure-tone average of thresholds in dB HL for 0.5 kHz, 1 kHz, 2 kHz, 3 kHz.

[4] SSQ = Speech, Spatial and Qualities of Hearing Scale total average score out of 10.

[5] Montreal Cognitive Assessment (MoCA) scores adjusted for years of education out of 30.

[6] Stroop score is calculated as the time difference (s) between form CW and form C.

[7] Trail-Making Test score is calculated as the time difference (sc) between form B and form A.

Overall, data from 23 younger adults ($M_{\text{Age}} = 23.7$ years, $\text{SD}_{\text{Age}} = 3.05$; 14 females) and 25 older adults ($M_{\text{Age}} = 71.46$ years, $\text{SD}_{\text{Age}} = 5.22$; 15 females) were included in the analyses. See Table 1 for participant demographics and scores obtained in the baseline assessment tasks. Participants provided informed written consent before participating in the study session(s) and were compensated financially for their time. This research was approved by the University Health Network (REB #18-5434) and University of Toronto (REB #37465) research ethics boards.

2.2. *Baseline Assessment Session*

As described in detail below, vision assessments included the Early Diabetic Retinopathy Study (ETDRS) acuity test (Ferris *et al.*, 1982) and the Pelli–Robson Contrast Sensitivity test (Pelli, Robson and Wilkins, 1988) to ensure normal visual acuity and contrast sensitivity. Hearing assessments included pure-tone audiometry following the American National Standards Institute standard (S3.6-1969) (objective measure to ensure normal audiometric hearing), the Dichotic Digits Test (DDT) (Musiek, 1983) (measure of central auditory processing), and the Speech, Spatial and Qualities of Hearing questionnaire (SSQ) (Gatehouse and Noble, 2004; subjective measure of hearing abilities). Cognitive assessments included the MoCA (Nasreddine *et al.*, 2005; to screen and exclude for cognitive impairment), Congruent–Incongruent Stroop Task (Form Color I and Form Color-Word (CW)) (Stroop, 1935; as a measure of inhibitory control), and the Trail-Making tests (Trail A and Trail B) (Reynolds, 2002; as a measure of visual search and executive functioning). The baseline assessment session took 1.5 to 2 h to complete. These measures were included to ensure that any age-related differences in audiovisual temporal processing were not influenced by clinically significant sensory or cognitive impairments through eligibility cutoffs (ETDRS, FTA, MoCA) and to more specifically characterize the sample within these domains of functioning (Pelli–Robson, DDT, SSQ, Stroop, Trails).

2.2.1. Vision Measures

ETDRS Visual Acuity Test. Participants read letters on a standardized eye chart from 4 m away until they could no longer read the letters, or until they made two errors in one line. This was done for each eye, and participants were encouraged to wear their usual corrective lenses. The logarithm of the minimal angle resolution (logMAR) score for each eye is based on the last line with less than two consecutive errors. An average logMAR score across both eyes was calculated and used for analyses (Ferris *et al.*, 1982). Based on the WHO International Classification of Diseases version 10, visual acuity is considered normal or near-normal in the range of −0.20 to 0.48 logMAR units. Thus, smaller logMAR scores indicate better visual distance acuity. All of the participants who were tested had visual acuity scores in the normal range.

Pelli–Robson Contrast Sensitivity Test. In a well-lit space, participants read letters printed in black against a white background from 4 m. The black letters decreased in contrast from left to right in each line from top (highest contrast) to bottom (lowest contrast). Participants stopped when they could no longer read the letters or if they made two errors in one line. This was completed for each eye separately and then for both eyes together. Participants were encouraged to wear their usual corrective lens. The logarithm of contrast sensitivity (logCS) score is based on the last line correct with less than two consecutive errors. The logCS scores for both eyes together were used for analyses. A logCS score above 1.52 (out of 2.00) indicates normal to near-normal contrast sensitivity for older adults (Mick *et al.*, 2021). Thus, larger logCS scores indicate better contrast sensitivity. All of the participants who were tested had scores within the normal range except for three older adults who scored below 1.52 logCS.

2.2.2. Hearing Measures

Pure-Tone Audiometry (PTA). The Hughson–Westlake procedure for audiometry was conducted using a Grason-Stadler 61 Clinical Audiometer (GSI-61; Grason-Stadler Inc., Eden Prairie, MN, USA) and Telephonics TDH-50P (Telephonics Corporation, Farmindale, NY, USA) headphones in a double-walled sound-attenuating booth (Industrial Acoustics Company, Inc., New York, NY, USA). The audiometric frequencies that were tested included 0.25, 0.5, 1, 2, 3, 4, 8 kHz in each ear. The BPTA of 0.5, 1,2, and 3 kHz was used for analyses. Pure-tone thresholds above 25 dB HL indicate impaired hearing, with larger values indicating poorer hearing. All older adult participants had normal PTAs.

Dichotic Digits Test (DDT). This test of suprathreshold auditory processing was completed in the same sound booth over headphones. The DDT test materials were obtained from a commercial CD audio recording (Auditect, St. Louis, MO, USA) and were presented with the audiometer connected to a CD player (Sony, Tokyo, Japan, CDP-CE375). The two channels required for the DDT test were calibrated for each participant before the start of the DDT test. On each trial, double-digit pairs were presented dichotically at 50 dB sensation level (SL). For example, a pair of digits, ‘1’ and ‘2’, would be presented to the left and right ear, respectively, immediately followed by another pair of digits, ‘3’ and ‘4’, presented to the left and right ear, respectively. Participants repeated back the digits in no particular order, but they were required to provide four numbers (Musiek, 1983). The total score is out of 100, calculated as the number of digits correctly repeated in 25 trials. A higher score indicates better performance.

Speech, Spatial, and Qualities of Hearing Scale. This questionnaire characterizes self-reported hearing abilities related to speech hearing (14 items), spatial hearing (17 items), and other qualities of sounds such as segregation and recognition of sounds and listening effort (18 items). For each item, a scenario was rated by the participant on a scale from 0 to 10 (i.e., poor to excellent). An average score of all items was calculated and used in the analyses. Higher scores indicate better self-reported hearing for speech, locating sounds, and other qualities of hearing. On average, older adults with clinically normal audiometric thresholds below 4 kHz have been shown to score on average 7.7 (SD = 1.2) out of 10 and younger adults have been shown to score on average 8.8 (SD = 0.6) out of 10 (Banh *et al.*, 2012).

2.2.3. Cognitive Measures

Montreal Cognitive Assessment. The MoCA was used to screen for MCI (Nasreddine *et al.*, 2005). Measures of visuospatial and executive functioning, naming, immediate and delayed recall, attention, language, abstraction, and orientation are assessed. A total score greater than or equal to 26 out of 30 points suggests normal cognition. All participants included in the analyses scored above 26 out of 30.

Congruent–Incongruent Stroop Task. The Stroop task measures inhibitory control (Stroop, 1935), one of many processes of executive functioning (Rey-Mermet and Gade, 2018). Trenerry *et al.*'s (1989) Stroop Neuropsychological Screening Test (SNST) was used. On the first Stroop form, participants identified the ink colours of asterisk symbols listed on a page. On the second Stroop form, participants identified the (incongruent) colour of words listed on a page. For example, the word 'red' may be printed in blue ink. Participants identified the colours of the ink as quickly and accurately as possible within 120 s. The Stroop task was scored as the time difference between the two Stroop forms. Time difference was calculated by subtracting the completion times (s) of the second form (coloured-words) from the first form (coloured-symbols). If the time difference (s) was more than 0 s, it indicates more time was spent on the incongruent Stroop form than on the congruent Stroop form. Thus, a higher value indicates poorer inhibitory control.

Trail-Making Test. The Trail-Making test characterizes visual search and executive functioning (Reitan, 1955). On the first form, participants used a pencil to connect circled numbers on a page in ascending numerical order. On the second form, participants connected circled numbers and letters, alternating between ascending number and letter series (e.g., '1–A2–B'). The score was determined as the time difference between the two forms by subtracting the completion times (s) of the second form (number-letter) from the first form (number-number). If the time difference (s) was positive and more than 0 s, it indicates more time was spent on the second form than on the first form. Thus, a higher value indicates poorer visual search and executive functioning. The normative mean for older adults on the first form in the age range of 70–74 has been reported to be 40.13 s ($SD = 14.48$), as well, the normative mean for older adults in the same age range for the second form has been reported to be 86.27 s ($SD = 24.07$) (Tombaugh, 2004).

2.3. Experimental Study Session

2.3.1. Setup

The experimental study session was conducted inside a single-walled sound-attenuating booth with the lights turned off to reduce visual cues in the testing environment. The visual and auditory stimuli used in the experimental study session were generated using MATLAB (Mathworks, Natick, MA, USA) and

Psychtoolbox extensions (Brainard, 1997; Pelli, 1997), and were presented from a MacBook Pro. The auditory stimuli were presented through Sennheiser HD 280 PRO headphones. The visual stimuli were presented on an LG 21.5′ FHD 5 ms GTG IPS LED monitor (resolution 1920 × 1080, 60 Hz).

2.3.2. Stimuli

The auditory stimulus was a tone that had a duration of 16.7 ms with 1-ms on and off ramping that was presented at 72 dB SPL (see Supplementary Material 1 for amplitude spectrum). The visual stimuli consisted of a white circle presented at 60 Hz and a luminance of 55.8 cd/m^2 on a black background for a duration of 16.7 ms. The inner and outer edge of the white circle extended 8.5° and 10° from the centre of the screen, respectively. Participants' chins rested on a chin rest fixed 58 cm away from the computer monitor. Participants were asked to wear their corrective lenses throughout the experiment. The onset and offset of the visual and auditory stimuli were verified with a photometer and an oscilloscope. The auditory stimulus and visual stimulus were identical across all experimental tasks (i.e., auditory-only, visual-only, and audiovisual SJ and TOJ tasks). During the auditory-only and audiovisual SJ and audiovisual TOJ tasks, the auditory stimuli were presented to both ears. During the visual-only, audiovisual SJ and audiovisual TOJ tasks, the two visual stimuli were positioned in the centre of the screen. A white fixation dot was centred on the screen at all times. Participants were told to maintain their gaze on the fixation dot.

2.3.3. Procedure

Sound Detection Verification Task. This task was completed before the experimental tasks began to ensure that participants were able to hear the auditory stimuli presented during the *experimental* tasks. The experimental auditory stimulus was randomly presented on nine out of 12 trials and participants were asked to respond either 'yes' or 'no' ('q' or 'p' on the keyboard, respectively) on each trial to indicate whether they heard or did not hear a sound. If participants did not respond 'yes' to at least seven out of nine times when the auditory stimulus was presented, and 'no' to at least two out of the three times the auditory stimulus was not presented, they were excluded from the study session. All the younger and older adult participants performed this task with at least 90% accuracy indicating that the auditory stimulus used in the main study was audible.

Auditory-Only and Visual-Only Simultaneous Judgement Tasks. The auditory-only and visual-only SJ tasks required participants to judge whether the two presented stimuli (two sounds for auditory-only or two circles for visual-only) occurred simultaneously. On each trial, the two stimuli were temporally separated with one of seven randomized SOAs: 0 ms (actual simultaneity), 16.7 ms, 33.4 ms, 50.1 ms, 83.5 ms, 100.2 ms, 133.6 ms. Five hundred milliseconds after the offset of the second stimulus, the response screen prompted participants to use a key press to indicate whether the stimuli were presented at the 'same' or 'different' time(s). Participants were given unlimited time to respond as they were instructed to be as accurate as possible with their judgements. Following their response, the next trial began after a variable amount of time ranging from 500 to 1500 ms. Each SOA was presented 20 times, resulting in 140 trials overall. There were two blocks with 70 trials each (each SOA was presented 10 times in each block). A break was provided after the first block. On average, each auditory and visual unisensory task took approximately 10–15 min to complete.

Audiovisual Simultaneous Judgement Task. Participants were presented with both an auditory stimulus and visual stimulus on each trial and were required to indicate whether the visual and auditory stimuli were presented simultaneously. The pair of visual and auditory stimuli were separated by one of 17 SOAs: 0 ms (actual simultaneity), −/+16.7 ms, −/+33.4 ms, −/+50.1 ms, −/+83.5 ms, −/+100.2 ms, −/+133.6 ms, −/+250.5 ms, −/+501 ms. For negative SOAs, the auditory stimulus was presented before the visual stimulus (auditory-leading trials); for positive SOAs, the visual stimulus was presented before the auditory stimulus (visual-leading trials). Each SOA was presented 20 times. Five hundred milliseconds after the offset of the second stimulus, the response screen prompted participants to indicate whether the stimuli were presented at the 'same' or 'different' time(s). Participants were given unlimited time to respond and were instructed to be as accurate as possible with their judgements. The next trial began a variable amount of time (500–1500 ms) after each response. In total, there were 340 trials, which were separated into four blocks with 85 trials in each block. In each block, each SOA was presented five times. Breaks were provided at the end of each block. On average, the audiovisual SJ task took 15–25 min to complete.

Temporal Order Judgement Task. The SOAs and trial procedure for the TOJ task were identical to the audiovisual SJ task, except for the response screen, which prompted participants to indicate whether the 'Beep' or 'Circle' was presented first. Breaks were provided at the end of each block (every 85th trial). On average, the audiovisual TOJ task took 15–25 min to complete.

Participants completed the auditory-only SJ, visual-only SJ, audiovisual SJ, and audiovisual TOJ in a pseudo-randomized order, such that the audiovisual TOJ task was either completed first or last. On average, the experimental study session took 1.5 to two hours to complete.

2.3.4. Statistical Analyses

The first section of the analyses used a series of mixed-factorial ANOVAs to examine the between-subjects effects of age group (younger and older) and the within-subject effects of task (visual-only SJ, auditory-only SJ, audiovisual SJ, audiovisual TOJ) for *proportional scores* (proportion of 'same' responses for SJs and proportion of 'visual-first' responses for TOJs) across the SOAs.

The second set of analyses used mixed-factorial and one-way ANOVAs to examine the between-subjects effects of age group (younger and older) and within-subject effects of task (visual-only SJ, auditory-only SJ, audiovisual SJ, audiovisual TOJ) on the measures obtained from fitting psychometric functions; i.e., the *TBW* and *PSS*. The TBW for the *audiovisual SJ* is the time range between the SOAs associated with the 75% proportion of 'same' responses on two separately fitted functions; the TBW for the *audiovisual TOJ* is the time range between the SOAs associated with the 75% and 25% proportion of 'visual-leading' responses on the fitted function. The PSS for the *audiovisual SJ* is the SOA associated with the intersection of the two separately fitted functions; the PSS, for the *unisensory SJ* and *TOJ tasks*, is the SOA associated with the 50% proportion of 'same' and 'visual-leading' responses on the fitted function. Each participant's fitted data was manually inspected for poor goodness of fit, $R^2 \leqslant 0.20$ (criteria adopted from Basharat *et al.*, 2019; see Supplementary Materials 2 for the same analyses but with a more conservative $R^2 \leqslant 0.5$ criterion implemented, where the results are largely maintained). In the visual-only SJ task, the performance measure (PSS) of one younger adult was replaced with the group mean of the respective age group and task due to poor goodness of fit. In the audiovisual TOJ task, the performance measures (TBW, PSS) of one younger adult and two older adults were replaced with the group means of the respective age group due to poor goodness of fit. The psychometric functions were fitted using the glmfit, glmval and curvefit functions in MATLAB (R2008a; Mathworks, Boston, MA, USA). Assumptions of homogeneity of variance were met for all ANOVAs ($p \geqslant 0.05$). Mauchly's test of sphericity was conducted and the Greenhouse–Geisser-corrected values are reported when necessary. Bonferonni *post-hoc* tests were conducted to examine pairwise differences for significant main and interaction effects.

The third set of analyses described *associations among the baseline unisensory and cognitive measures and the performance measures* from the unisensory and audiovisual SJ and audiovisual TOJ tasks. Pearson's correlation coefficients were conducted for each association and for younger and older adult groups separately. p-values were adjusted with the false discovery rate to correct for multiple comparisons (p_{FDR}). Statistical significance was determined using a significance level of $p < 0.05$ for all analyses and comparisons.

3. Results

3.1. Proportion Scores

3.1.1. Auditory-Only and Visual-Only Simultaneity Judgement Tasks

A 2 (age group: younger, older) × 2 (task: auditory-only, visual-only) × 7 (SOA: 0, 16.7, 33.4, 50.1, 83.5, 100.2, 133.6 ms) mixed-factorial analysis of variance (ANOVA) was conducted on the proportion of responses that participants responded that the stimuli occurred at the 'same' time (Fig. 1). A main effect of age group was found, $F_{1,46} = 13.88$, $p < 0.001$, $\eta^2 = 0.090$, indicating that older adults ($M = 0.32$, SD = 0.37) were more likely than younger adults ($M = 0.20$, SD = 0.32) to respond 'same'. There was a main effect of task, $F_{1,46} = 32.88$, $p < 0.001$, $\eta^2 = 0.149$, with fewer 'same' responses in the auditory-only SJ task ($M = 0.19$, SD = 0.33; Fig. 2) than in the visual-only SJ task ($M = 0.34$, SD = 0.36). There was also a main effect of SOAs, $F_{2.64,121.40} = 469.10$, $p < 0.001$, $\eta^2 = 0.687$ where increasingly larger SOAs were associated with fewer 'same' responses. There was a significant interaction between task and age group, $F_{1,46} = 7.40$, $p < 0.001$, $\eta^2 = 0.038$. The *post-hoc* test indicated that in the auditory-only SJ task, older adults showed similar proportion of 'same' responses ($M = 0.21$, SD = 0.34) as younger adults ($M = 0.16$, SD = 0.32), $p = 0.250$, but in the visual-only SJ task, older adults were significantly more likely to respond 'same' ($M = 0.43$, SD = 0.38) than younger adults ($M = 0.24$, SD = 0.32), $p < 0.001$. There was also a significant interaction between task and SOA, $F_{2.44,112.07} = 40.72$, $p < 0.01$, $\eta^2 = 0.159$, where the proportion of 'same' responses were higher for visual-only SJ compared to auditory-only SJ at SOAs from 16.7 ms to 50.1, 100.2 ms and 133.6 ms, $p < 0.01$ (no significant differences at 0 ms and 83.5 ms, $p > 0.05$). Lastly, there was a significant interaction between age group and SOA, $F_{2.64,121.40} = 6.50$, $p < 0.01$, $\eta^2 = 0.030$, such that the proportion of 'same' responses was greater for older compared to younger adults for every SOA $p < 0.05$, apart from 0 ms, $p > 0.05$. No other interaction effects were significant.

3.1.2. Audiovisual Simultaneity Judgement Task

A 2 (age group: younger adults, older adults) × 17 (SOA: 0, −/+16.7, −/+33.4, −/+50.1, −/+100.2, −/+133.6, −/+250.5, −/+501 ms) mixed-factorial ANOVA was conducted on the proportion of 'same' responses in the audiovisual SJ task (Fig. 2). A main effect of age group was found, indicating that older adults responded 'same' more often ($M = 0.72$, SD = 0.30) than younger adults ($M = 0.61$, SD = 0.33) overall, $F_{1,46} = 6.58$, $p = 0.014$, $\eta^2 = 0.068$. There was also a main effect of SOA, $F_{4.62,212.36} = 154.96$, $p < 0.001$, $\eta^2 = 0.624$, where increasingly larger SOAs were associated with fewer 'same' responses. There was no interaction between age group and SOA, $p > 0.05$.

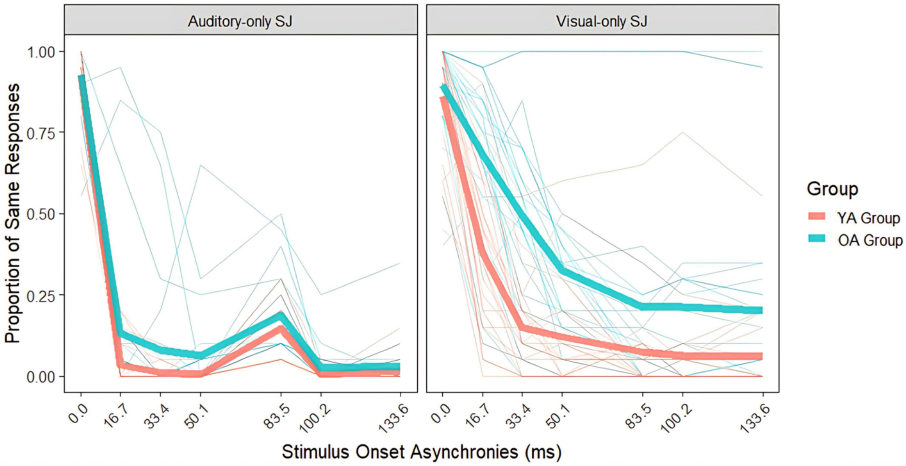

Figure 1. Proportion of 'same' responses in younger and older adults across stimulus onset asynchronies (SOAs) in the auditory-only (left) and visual-only (right) simultaneity judgement (SJ) tasks. The red lines represent younger adults and blue lines represent older adults with the bolded lines being the averaged proportion of 'same' responses for each group and the thinner lines representing individual participant data.

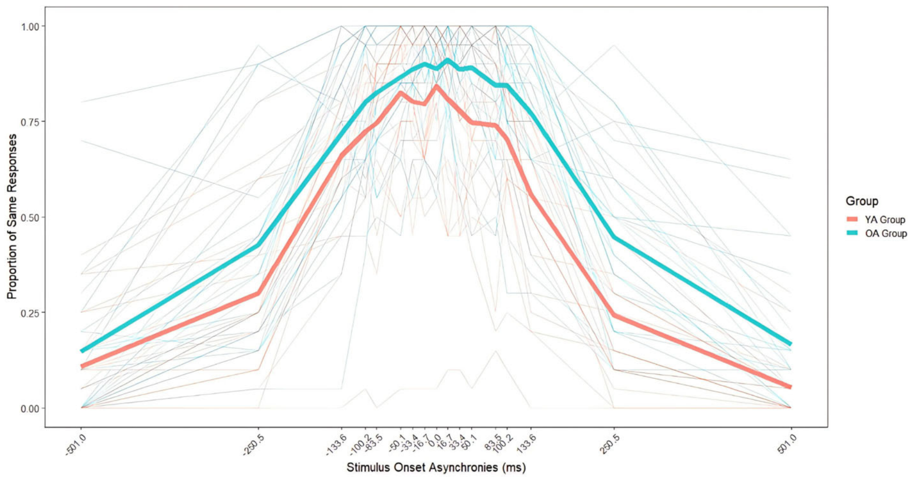

Figure 2. The line graph shows the proportion of 'same' responses for younger adults (red) and older adults (blue) across the stimulus onset asynchronies (SOAs) in the audiovisual simultaneity judgement (SJ) task. Negative SOAs indicate the auditory stimulus was presented before the visual stimulus, and positive SOAs indicate the visual stimulus was presented before the auditory stimulus. The bolded lines are the averaged proportion of 'same' responses for each age group and the thin lines represent individual participant data.

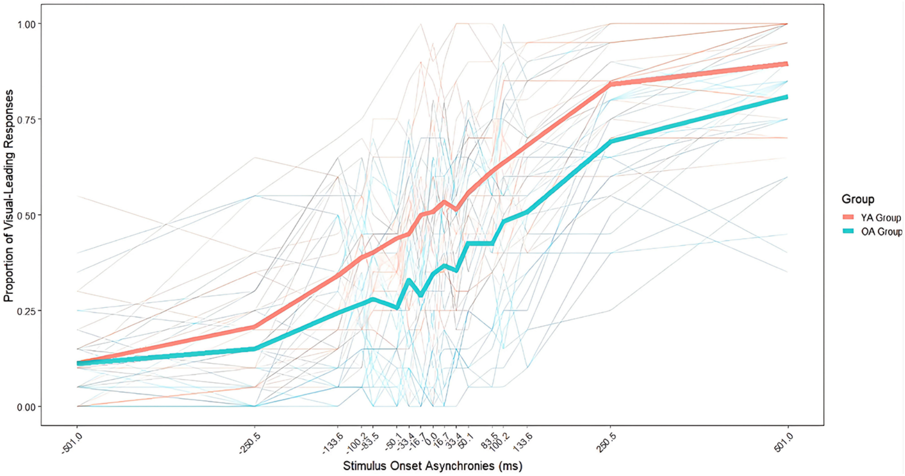

Figure 3. Proportion of 'visual-leading' responses for younger adults (red) and older adults (blue) across the stimulus onset asynchronies (SOAs) in the audiovisual temporal order judgement (TOJ) task. Negative SOAs indicate the auditory stimulus was presented before the visual stimulus, and positive SOAs indicate the visual stimulus was presented before the auditory stimulus. The bolded lines are the averaged proportion of 'visual-leading' responses for each age group and the thin lines represent individual participant data.

3.1.3. Audiovisual Temporal Order Judgement Task

A 2 (age group: younger adults, older adults) × 17 SOA (0, −/+16.7, −/+33.4, −/+50.1, −/+100.2, −/+133.6, −/+250.5, −/+501 ms) mixed-factorial ANOVA was conducted on the proportion of 'visual-first' responses in the audiovisual TOJ task (Fig. 3). There was a significant main effect of age group, $F_{1,46} = 9.58$, $p < 0.003$, $\eta^2 = 0.100$, indicating that older adults made fewer 'visual-leading' judgements ($M = 0.37$, SD = 0.27) compared to younger adults ($M = 0.51$, SD = 0.27) overall. A main effect of SOA was also found, $F_{4.64,213.55} = 80.51$, $p < 0.001$, $\eta^2 = 0.448$, where increasingly positive SOAs were associated with more 'visual-leading' responses. No significant interaction between age group and SOA was found, $p > 0.05$.

3.2. Performance Measures

3.2.1. Temporal Binding Window

A 2 (age group: younger adults, older adults) × 2 (task: audiovisual SJ task *vs* audiovisual TOJ) mixed-factorial ANOVA was conducted on the TBW values (Fig. 4). Overall, the main effect of age group approached significance, $F_{1,46} = 3.91$, $p = 0.054$, $\eta^2 = 0.043$, which suggested that older adults had a wider TBW ($M = 470$ ms, SD = 827 ms) than younger adults ($M = 210$ ms, SD = 279 ms). The TBWs between the audiovisual SJ task ($M = 263$ ms, SD = 178 ms) and audiovisual TOJ task ($M = 428$ ms, SD = 881 ms) were

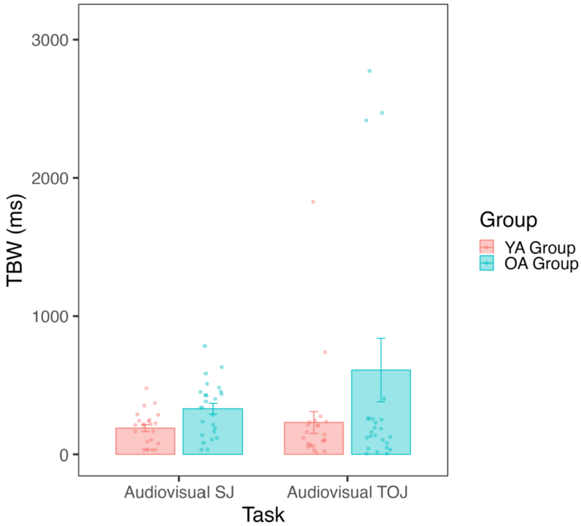

Figure 4. Temporal binding window (TBW) values for younger and older adults for the audiovisual simultaneity judgement (SJ) and temporal order judgement (TOJ) tasks. Bar graphs represent group averages and dots represent individual participant data. Error bars represent standard error of the mean.

not significantly different from each other, $p > 0.05$. No interaction between age group and task was found, $p > 0.05$.

3.2.2. *Point of Subjective Simultaneity*

The PSSs of the *unisensory SJ tasks* were analyzed with a 2 (age group: younger adults, older adults) x 2 (task: auditory-only SJ, visual-only SJ) mixed-factorial ANOVA (Fig. 5). There was a significant main effect of age group, $F_{1,46} = 5.46$, $p = 0.024$, $\eta^2 = 0.064$ indicating that older adults had a larger PSS ($M = 24.3$ ms, SD $= 29.5$ ms) than younger adults overall ($M = 12.7$ ms, SD $= 20.3$ ms). There was also a significant main effect of task, $F_{1,46} = 29.87$, $p < 0.001$, $\eta^2 = 0.214$, indicating that the visual-only SJ task had a larger PSS ($M = 30.4$ ms, SD $= 31.7$ ms) than the auditory-only SJ task ($M = 7.05$ ms, SD $= 9.21$ ms). No interaction between age group and task was found, $p > 0.05$.

The PSSs of the *audiovisual tasks* were analyzed with a 2 (age group: younger adults, older adults) x 2 (task: audiovisual SJ, audiovisual TOJ) mixed-factorial ANOVA (Fig. 5). There was a significant main effect of age group, $F_{1,46} = 5.06$, $p = 0.029$, $\eta^2 = 0.046$, indicating that older adults had a larger PSS ($M = 42.5$ ms, SD $= 125$ ms) than younger adults ($M = -2.21$ ms, SD $= 84.5$ ms). Across younger and older adults, the audiovisual SJ PSS ($M = 0.26$ ms, SD $= 50.9$) was not significantly different from the audiovisual TOJ PSS ($M = 41.9$ ms, SD $= 144$ ms), $p > 0.05$. There was a

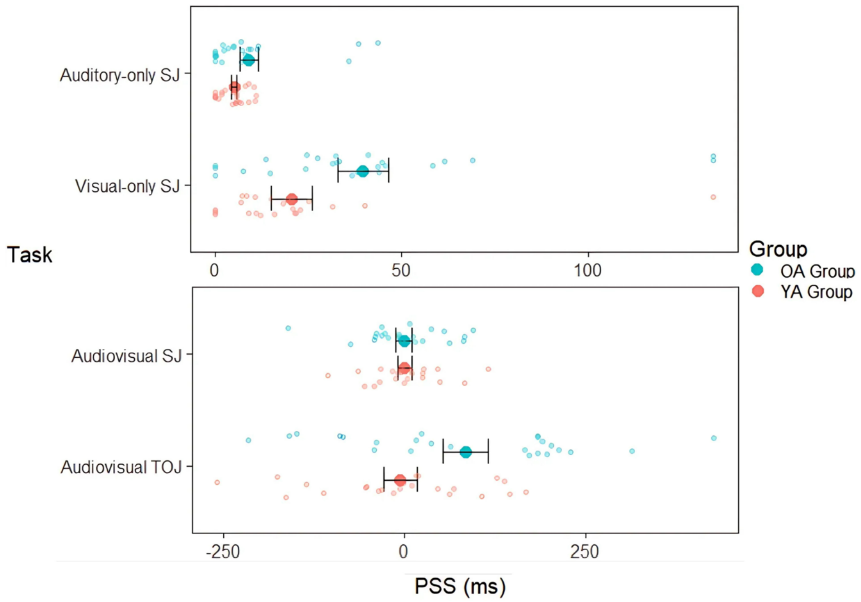

Figure 5. Point of subjective simultaneity (PSS) values for younger and older adults in the unisensory simultaneity judgement (SJ) tasks (top) and the audiovisual simultaneity judgement and temporal order judgement (TOJ) tasks (bottom). The larger, solid dots represent the averaged PSSs of each SJ and TOJ task for younger and older adults. The smaller dots represent individual participant data. Error bars represent standard error of the mean.

significant interaction between age group and task, $F_{1,46} = 4.16$, $p = 0.047$, $\eta^2 = 0.048$. The *post-hoc* test showed that younger adults had a smaller PSS ($M = -5.24$ ms, SD = 111 ms) than older adults ($M = 85.3$ ms, SD = 158 ms) in the audiovisual TOJ task, $p = 0.027$, but not in the audiovisual SJ task, $p > 0.05$. *Post-hoc* tests also showed that older adults had a larger PSS in the audiovisual TOJ task than in the audiovisual SJ task ($M = -0.25$ ms, SD = 54.7 ms), $p = 0.032$. Meanwhile, younger adults showed similar PSS values in the audiovisual TOJ task ($M = -5.24$ ms, SD = 111 ms) and in the audiovisual SJ task ($M = 0.81$ ms, SD = 47.6 ms), $p > 0.05$.

3.3. Associations Among Baseline Visual, Auditory, Cognitive Abilities and Performance Measures of Unimodal SJ, Audiovisual SJ, and Audiovisual TOJ

Within younger adults and within older adults, no significant correlations after false discovery rate corrections were found between standard baseline measures of sensory functioning, unisensory temporal processing task performance (visual-only and auditory-only SJ), or cognitive abilities with the experimental performance measures (TBW and PSS of the audiovisual SJ task and the TBW of the audiovisual TOJ task, all p_{FDR} values > 0.05).

4. Discussion

This study examined (1) age-related differences in performance on the audiovisual SJ and TOJ tasks and (2) associations among the unisensory (baseline sensory tests and auditory/visual-only SJs), cognitive, and audiovisual (SJ and TOJ) measures in healthy younger and older adults. Overall, the results demonstrated that even when carefully screening for impairments in individual sensory and cognitive abilities by using strict eligibility criteria based on self-report and objective behavioural tests, older adults still showed a wider TBW and a larger PSS than younger adults in the audiovisual TOJ tasks and a larger TBW (but not PSS) in the audiovisual SJ task. Also, within this healthy older and younger adult sample, performance on individual sensory and cognitive baseline tests was not associated with measures of audiovisual temporal processing. Altogether, the findings support the view that audiovisual processes, and particularly temporal order discrimination, is different in older and younger adults, even in those with sensory and cognitive functioning within clinically normal limits. This suggests that any inconsistences in reported age-related effects in the previous literature may not be completely explained by conflating sensory and cognitive impairments, but perhaps other factors such as the parameters of the stimuli and the nature of the task.

4.1. Age-Related Differences in the Unisensory SJ Tasks and Associations with Audiovisual Synchrony Judgements

In the visual-only SJ task, older adults showed a larger proportion of 'same' responses than younger adults, but not in the auditory-only SJ task, suggesting that age-related temporal processing differences were most apparent for the visual task. Older adults showed larger PSSs than younger adults in the auditory-only and visual-only SJ tasks, with both age groups showing a larger PSS in the visual-only SJ task than in the auditory-only SJ task. These results are consistent with known age-related declines in unisensory temporal processing (Humes *et al.*, 2009; Stevenson *et al.*, 2018) and poorer temporal precision of visual relative to auditory processing (Gori *et al.*, 2012; Saija *et al.*, 2019). Few studies, however, have considered how unisensory temporal processing may be associated with audiovisual temporal processing (e.g., relating unisensory to audiovisual SJ and TOJ performance). In this study, we did not observe associations between the unisensory SJs and the audiovisual SJ and TOJ performance measures. This finding aligns with those of a study by Stevenson *et al.*, (2018), which did not find associations between unisensory TOJs and audiovisual SJ performance measures in older and younger adults (but see De Boer-Schellekens and Vroomen, 2014). Overall, this suggests that auditory and visual temporal processing abilities in isolation are not likely to exclusively explain age-related differences in multisensory temporal processing outcomes, suggesting that age-related differences may be better explained by differences in suprathreshold central sensory processing and integration processes.

In the current study, the same stimulus characteristics (e.g. auditory amplitude levels, visual contrast levels) were used for all participants and it was ensured that the stimuli were visible and audible for all participants. Future studies may, instead, consider equating the individual unisensory thresholds to ensure that stimuli are detected at equal levels of performance across participants (Scurry *et al.*, 2021). For example, a psychophysical detection task may be used to obtain the absolute threshold of auditory stimuli (e.g., varying in amplitude) uniquely for each individual. This individual's specific threshold value could then be used in the audiovisual SJ and TOJ tasks. Using the absolute threshold as a benchmark to scale the auditory and visual inputs may also help ensure that the reliability of the signal is not too high (too distinct so that audiovisual processing does not occur due to sensory dominance), or too low (too weak so that participants cannot detect it). This psychophysical approach could further help disentangle whether age-related differences in audiovisual temporal processing are due to differences in integrative processes, or differences in how the unisensory stimuli were processed independently (Chan *et al.*, 2014a, b).

4.2. Age-Related Differences in the Audiovisual SJ and TOJ Tasks

The current results showed that older adults had a larger proportion of 'same' and 'auditory-leading' responses than younger adults in the audiovisual SJ and TOJ tasks, respectively. As well, the TBW was wider in older adults than in younger adults in both audiovisual SJ and TOJ tasks. The audiovisual TOJ PSS was also significantly larger in older adults than in younger adults. No age-related differences were found for the audiovisual SJ PSS. Furthermore, older adults showed a larger PSS in the audiovisual TOJ task than in the audiovisual SJ task, whereas younger adults showed comparable PSSs between the audiovisual SJ and TOJ tasks.

In terms of the TBW, the current findings align with past studies examining age-related differences in either audiovisual SJs or TOJs, with both tasks demonstrating larger TBWs in older adults compared to younger adults (Chan *et al.*, 2014a, b; Noel *et al.*, 2016; Setti *et al.*, 2011). However, the few other studies that conducted within-subject comparisons of the TBW for SJ and TOJs in older and younger adults have shown mixed findings. For instance, Bedard and Barnett-Cowan (2016) found that older adults have a significantly wider TBW than younger adults in the audiovisual TOJ task, but not the audiovisual SJ task. Conversely, Basharat *et al.* (2018, 2019) did not find significant age-related differences in the TBWs in either audiovisual SJ or TOJ task.

In terms of the PSS, the current findings only partially align with past studies. Consistent with the current study, using the audiovisual SJ task, Noel *et al.*

(2016) also did not observe significant age-related changes in the PSS across the lifespan in their sample of younger and older adults. Unlike the current study, using the audiovisual TOJ task, Fiacconi *et al.* (2013) did not observe significant differences in the PSS between younger and older adults.

The inconsistent age-related differences in the TBW and PSS found across studies may be partially explained by differences in the unisensory and/or cognitive abilities of the participants. Similar to most previous studies, the current study pre-screened younger and older adults for hearing, vision and cognitive impairments using self-report questions. However, previous studies were inconsistent in terms of whether and how hearing, vision, and cognitive abilities were verified with objective tests. Subjective assessments of abilities may not always map onto objective performance on domain-specific tasks. For example, during the pre-screening process in the present study, 28 older adults self-reported healthy hearing; however, during the in-person baseline assessment session, three of these participants demonstrated measurable audiometric hearing loss and they were subsequently excluded from the analyses.

4.3. Associations Between Sensory and Cognitive Abilities with Audiovisual Simultaneity and Temporal Order Judgements

We did not observe significant associations among the auditory, visual, and cognitive abilities and the audiovisual SJ and TOJ performance measures. This suggests that, within this sample of healthy younger and older adults, age-related differences in audiovisual temporal processing were not strongly associated with sensory acuity (visual acuity, pure-tone audiometric thresholds) or general cognitive abilities (e.g., MoCA). These results may not be surprising given that the strict study eligibility criteria resulted in a sample of older adults who had very high levels of sensory and cognitive functioning. Specifically, the older adults in the current sample were only included in the study if they performed within normal to upper ranges of cognitive functioning, audiometric hearing, and visual acuity. While there was a range of performance abilities observed for each of the baseline cognitive and sensory tasks (i.e., Stroop task, Trail-Making test, contrast sensitivity, DDT, and the SSQ), within this range of variability sampled, cognitive and sensory associations with the audiovisual TBW and PSS were not observed. This suggests that age-related differences in audiovisual temporal processing may not be due to sensory abilities or cognitive abilities within normal ranges. Nevertheless, it remains that even within this high-performing healthy older adult sample, age-related differences in performance measures such as wider TBWs and larger TOJ PSSs persist when making temporal order judgements.

4.4. Limitations and Future Directions

There are several reasons to carefully characterize individual participant characteristics across factors that may be expected to influence perceptual performance. One reason is to *control* for these factors as a method of limiting their influence on the observed experimental outcomes. The other is to better understand whether and how these factors actually *influence performance*. While both are certainly meritorious, in the current study we focused on the former (characterize to control) rather than the latter (characterize to measure the influence of). The motivation for this was that most studies in the literature have not previously controlled for these factors using thorough standardized measures and as such, this could have influenced the inconsistencies across studies. Reassuringly, the current study demonstrates that even when these factors are carefully controlled for, several age-related differences persist. In contrast, taking the approach of not controlling for factors such as visual acuity/contrast sensitivity or hearing abilities, but rather establishing a very liberal eligibility criteria to allow for a range of participant abilities and deficits, may introduce confounds. In which case, perceptual effects can no longer be attributed to MSI specifically, but instead to other factors such as visual impairments or cognitive impairments beyond which would be age-typical. However, future studies using a large and more heterogeneous sample may allow for a better understanding of how various individual differences contribute to audiovisual simultaneity and TOJs.

It is also notable that in the current study the baseline, standardized assessments of hearing and cognitive functioning were only conducted in older adults, whereas self-report screening and overall physical and cognitive health criteria was used to determine eligibility for both older and younger adults. This was in part due to the fact that self-reported sensory impairments are typically less common and reliability reported in younger adults and because some of the cognitive tests have been primarily validated for older adults (e.g. MoCA). Future research should consider conducting the same set of baseline measures on both younger and older adults. Finally, it is also possible that the effects of controlling for sensory and cognitive functioning in the context of audiovisual processing and multisensory integration more broadly speaking may also be related to the nature of the stimuli used and/or the nature of the task (Bak *et al.*, 2021; Love *et al.*, 2013; Petrini *et al.*, 2020) and therefore exploring paradigms such as multisensory illusions, or stimuli that include, for example, contextual cues could be considered.

5. Conclusion

This study examined age-related differences in the audiovisual SJ and TOJ tasks and their associations with unisensory and cognitive abilities. Within this high-performing healthy older adult sample, older adults were found to have a wider TBW across the audiovisual SJ and TOJ tasks and a larger PSS compared to younger adults in the audiovisual TOJ task. No associations were found among the unisensory, cognitive, and audiovisual measures. Overall, this study showed that (1) the temporal binding window for audiovisual events was wider for healthy older adults than younger adults, (2) perceived simultaneity of audiovisual events also differed with age, depending on the task, and (3) older adults' ability to combine and perceive sensory inputs as separate events and to discern the temporal order of events were not associated with unisensory and cognitive abilities within verified normal ranges of functioning. These findings may have important implications for older adults' everyday behaviours when performing complex tasks that require precise temporal sensitivity for multisensory events (e.g., communication, mobility).

Supplementary materials

Data is available on https://doi.org/10.1163/22134808-bja10162 under Supplementary Materials.

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