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Research Article

Age-Related Changes in Audiovisual Simultaneity Perception and Their Relationship With Working Memory

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Abstract

Objectives: Perceiving simultaneity of a visual and an auditory signal is critical for humans to integrate these multisensory inputs effectively and respond properly. We examined age-related changes in audiovisual simultaneity perception, and the relationships between this perception and working memory performances with aging.

Methods: Audiovisual simultaneity perception of young, middle-aged, and older adults was measured using a simultaneity judgment (SJ) task, in which a flash and a beep were presented at 1 of 11 stimulus-onset asynchronies (SOAs). Participants judged whether these two stimuli were perceived simultaneously. Precision of simultaneity perception, the SOA corresponding to the point of subjective simultaneity (PSS), and response errors at each SOA were estimated using model fitting. The precision and PSS are associated with multisensory perception per se, whereas the response error reflects executive ability when performing the SJ task. Visual working memory of the same middle-aged and older adults was measured using the Cambridge Neuropsychological Test Automated Battery (CANTAB) beforehand.

Results: Compared to young adults' performances, middle-aged and older adults showed a decreased precision, a shift of PSS toward the visual-leading SOAs, and increased response errors at the visual-leading SOAs. Among these changes, only the increased response errors correlated with worse spatial recognition memory in middle-aged and older adults.

Discussion: Age-related decrements in audiovisual simultaneity perception start from middle age and are manifested in both perceptual and executive parameters. Furthermore, higher-order executive ability is plausibly a common cause for age-related degenerations in the audiovisual simultaneity perception and visual working memory.

Keywords: Audiovisual simultaneity window, Cross-modal temporal sensitivity, Simultaneity judgments, Working memory

When crossing a street, for example, seeing a moving car and hearing its engine's revving noise can help people notice the car, and accordingly, decide to keep walking or stop. Such daily experiences support the idea that integrating multisensory information gives rise to a more accurate and precise perception, as well as a faster response regarding an object (e.g., Alais & Burr, 2004; van der Burg et al., 2008; Chen & Spence, 2011; Ernst & Banks, 2002; Miller, 1991; Vroomen & de Gelder, 2000). For older adults, it has been demonstrated that some cognitive performances, such as recognition of facial expressions and auditory objects, and the speed of visual object detection or discrimination, were improved following audiovisual integration as compared to unisensory conditions (e.g., Chaby et al., 2015; Heikkilä et al., 2018; Laurienti et al., 2006; Peiffer et al., 2007; see de Dieuleveult et al., 2017; Freiherr et al., 2013, for reviews). On the contrary, impaired audiovisual integration abilities have been found in age-related cognitive degeneration and disorders, such as mild cognitive impairment and Alzheimer's disease (Chan et al., 2015; Murray et al., 2018; Wu et al., 2012). Roberts and Allen (2016) proposed three hypotheses regarding the relationships between the declines in perception and cognition with aging: impoverished sensory information increases cognitive load, poor cognitive resources narrow down the bandwidth of perceptual processing, or there is a third factor associated with aging as a common cause for perception and cognition. The relations between multisensory perception and cognition therefore provide critical understanding regarding the systematic changes in the aging brain, which has been rarely studied to date (e.g., Baum & Stevenson, 2017). Here we aimed to examine this issue by characterizing the detailed changes of audiovisual simultaneity perception with aging and relating it to older adults' working memory performances, given the fact that working memory has been shown to be declined with aging (Hedden & Gabrieli, 2004).

In order to accurately integrate sight and sound originating from the same source, perceiving their simultaneous onset provides a critical cue (Stein & Meredith, 1993; Welch & Warren, 1980). Nevertheless, inconsistent results of age-related changes in audiovisual simultaneity perception have been reported (see Brooks et al., 2018, for a review). Some studies demonstrated that older adults tolerated a larger range of stimulus-onset asynchronies (SOAs) between visual and auditory signals when perceiving them as simultaneous compared to young adults; that is, the precision of audiovisual simultaneity perception decreases with age (Bedard & Barnett-Cowan, 2016; Chan et al., 2014a; Noel et al., 2016; Setti et al., 2011; Stevenson et al., 2018; Virsu et al., 2003). In contrast, other studies reported that the precision of audiovisual simultaneity perception, as well as the condition which the participants most likely judged the two signals being simultaneous (i.e., the point of subjective simultaneity, PSS), remained constant until around 80 years old (Basharat et al., 2018; Bedard & Barnett-Cowan, 2016; Fiacconi et al., 2013). These contrasting results therefore motivated us to improve the methodology when measuring audiovisual simultaneity perception in different age groups.

A method commonly used to measure adults' audiovisual simultaneity perception is the simultaneity judgment (SJ) task. On each trial, a visual flash and an auditory beep are presented at predesignated SOAs (auditory-leading, simultaneous, or visual-leading), and participants have to judge whether the two stimuli were perceived at the same or different times. The proportion of simultaneous responses increases when the two stimuli are presented closer in time, forming a Gaussian distribution as a function of SOA. In order to estimate the asymptote of the Gaussian distribution (i.e., nonsimultaneous responses were made reliably), we used a larger range of SOAs in the current study (±600 ms) as compared to previous studies (±300 ms, e.g., Bedard & Barnett-Cowan, 2016; Noel et al., 2016; Stevenson et al., 2018).

When fitting individual data and estimating critical parameters that determine a participant's audiovisual simultaneity perception, we used a model specifically designed for the SJ task developed by García-Pérez and Alcalá-Quintana (2012; see also Alcalá-Quintana & García-Pérez, 2013) rather than general mathematical functions used in previous studies (Basharat et al., 2018; Bedard & Barnett-Cowan, 2016; Noel et al., 2016; Stevenson et al., 2018). García-Pérez and Alcalá-Quintana's model assumes that sensory signals are processed independently in each sensory pathway, and then reach a central comparator that decodes their arrival times. Hence, the perceived asynchrony between the two signals is determined by the processing time and variance in each sensory pathway, giving rise to a probability distribution rather than a constant. A person's precision of audiovisual simultaneity perception corresponds to a threshold that, if the perceived asynchrony in a trial is smaller than the threshold, then a simultaneous response would be made. Note that this model also assumes that a person may sometime misreport his or her judgment because of eye blinks, lapse of attention, and errors of motor execution during the testing period. Hence, this model generates eight parameters that account for a person's performance in the audiovisual SJ task. The processing variability of visual and auditory signals (λV and λA, respectively) and their processing time difference ($\tau = \tau A - \tau V$) are three parameters associated with unisensory processing. The precision (or threshold) of simultaneity perception (labeled as δ) and the PSS correspond to half of the width and the midpoint of the distribution at the 50% simultaneous response, respectively. These two parameters are associated with audiovisual perceptual processing. Finally, the participants' misreporting "simultaneous" in the auditory-leading trials (εAF) and in the visual-leading trials (εVF), or misreporting "not simultaneous" in the 0-ms trials (εS) are three parameters associated with the participant's executive functions when performing the SJ task.

In the current study, the goal was to understand the link between audiovisual simultaneity perception and working memory with aging. To do so, we measured the age-related change of audiovisual simultaneity perception by testing three age groups: young, middle-aged, and older adults. Using the SJ task and García-Pérez and Alcalá-Quintana's (2012) model, three unisensory parameters (λV, λA, and τ), two perceptual parameters (δ and PSS), and three executive parameters (εAF, εVF, and εS) determining the performance in the audiovisual SJ task were estimated. We then examined the relations between audiovisual simultaneity perception and working memory performances measured by the *Cambridge Neuropsychological Test Automated Battery* (CANTAB). Given that each parameter generated from the SJ task corresponds to a particular level of information processing, its correlation with the working memory performances would provide critical insights regarding the link between multisensory perception and cognition (Roberts & Allen, 2016). This correlation analysis mainly focused on the middle-aged and older adults in order to avoid being misrepresented by young adults' age range and ceiling performance in the CANTAB (see below).

Method

Participants

Three age groups of participants were tested: 40 young adults (21 females, mean age = 26.1 years, range = 20–34 years), 36 middle-aged adults (31 females, mean age = 60.5 years, range = 53–64 years), and 39 older adults (28 females, mean age = 69.4 years, range = 65–81 years). The lower boundary of age in the older group was defined in accordance with the suggestion of World Health Organization (n.d.) for developed countries. Additional eight participants (two middle-aged and six older adults) were tested but not included in the final analysis because their scores in the Montreal Cognitive Assessment (MoCA, see below) were lower than 26, suggesting that their cognitive functions were degraded. The participants were recruited from Taipei metropolitan areas. All of the participants went through a visual acuity test and had normal hearing by self-report. Written consent from all of the participants was obtained before starting the study. All of the participants were naïve regarding the purpose of the study. The study was approved by Institutional Review Board of National Taiwan University Hospital (IRB number: 201212161RIND, 201503037RINB).

An analysis using G*Power (version 3.1.9.2; Faul et al., 2007) for one-way analysis of variance (ANOVA) suggests that when testing 90 participants (30 in each age group) with $\alpha = 0.05$ and power = 0.95, the main effect of age group would reach effect size = 0.42 (i.e., a large effect). Stevenson et al. (2018) tested five age groups, including children (N = 24), adolescents (N = 22), younger adults (N = 26), middle-aged adults (N = 31), and older adults (N = 35), and the effect size of the main effect of age group was 0.39 ($\eta_p^2 = 0.13$ was reported). This therefore suggests that testing at least 30 participants in each age group in the current study would lead to an effect size comparable to those reported in previous studies.

Design and Procedure

All of the participants performed a measure of audiovisual simultaneity perception using the audiovisual SJ task. Before starting the experiment, each participant tried whether he/she could better see the visual flash with or without his/her own optical glasses. The participant was then tested in the condition with clearer flash perception. After the participant completed the audiovisual SJ task, we tested the participant's visual acuity in the same visual condition using a Landolt C Chart and asked each participant to stand 5 m away from the chart. The participants in the middle-aged and older adults groups also took assessments of their cognitive functions using the MoCA and CANTAB, and gait performance (for the purpose of another study not reported here).

Audiovisual SJ task

Participants were seated in a dimly-lit room, facing a 19-inch laptop monitor (1440 * 900 pixels) with a distance of approximately 50 cm. A gray ring with 2° inner diameters and 0.6° thickness was displayed in the center of a black background on the monitor throughout the experiment. The visual stimulus was a 2° white disc presented in the gray ring for 17 ms (one frame at the 60 Hz refresh rate). The auditory stimulus (white noise with a loudness of 60 dB SPL) was presented from speakers placed on either side of the monitor (the room had a background noise level of 30 dB SPL). The duration of the beep was 17 ms with 2 ms on and off ramping. The presentation of the stimuli was controlled by Matlab (MathWorks Inc., Natick, MA) and Psychtoolbox extensions (Brainard, 1997; Pelli 1997).

Two factors were manipulated: age group (young, middle-aged, and older) and SOA (−600, −400, −300, −200, −100, 0, 100, 200, 300, 400, and 600 ms), where negative values indicated that the auditory beep was presented first and positive values indicated that the visual flash was presented first. The SOA between the flash and beep was confirmed using an oscilloscope. Each SOA was tested twice in a block in a random order and all of the participants completed 10 blocks, giving rise to 220 trials in total. Participants were allowed to take a short break between blocks and typically took 30 min to complete the experiment.

During the experiment, participants were instructed to fixate on the ring. The participants' task was to orally report "yes" if they perceived the flash and beep at the same time, or "no" if they perceived the flash and beep at different times. An experimenter sat beside the participant and keyed the answers into a computer. The experimenter also ensured that the participants fixated on the ring, and if not, asked them to stop for a short break.

A practice session designed to ensure that the participants understood how the task was conducted prior to the main experiment. There were eight trials, four with 0 ms SOA and the remaining four with longer SOAs (−600, −400, 400, or 600 ms). Participants needed to achieve an 85% accuracy (i.e., no more than one error) within three attempts in order to proceed.

Montreal Cognitive Assessment

MoCA is a well-developed quick assessment of cognitive functions that includes attention, visual spatial ability, short-term memory, working memory, language, executive functions, and knowledge of facts. The test scores of MoCA ranges from 0 to 30. Having a score of 26 or above is considered cognitively normal (Nasreddine et al., 2005). The participants in the middle-aged and older group who were included in the final analyses had reached this criterion.

Cambridge Neuropsychological Test Automated Battery
Five visual working memory subtests that assess three important aspects of visual working memory in the CANTAB were used (see Supplementary Appendix A). Two of them assess visual pattern working memory: Pattern Recognition Memory (PRM) and Delayed Matching to Sample (DMS), another two assess visual spatial working memory: Spatial Recognition Memory (SRM) and Spatial Working Memory (SWM), and the last one assesses visual spatiotemporal working memory: Spatial Span (SSP). Five behavioral indices associated with each test were measured and used to assess the relations between audiovisual simultaneity perception and working memory performances. Only middle-aged and older adults were tested because of two reasons: First, these tasks were too easy for healthy young adults, and their performances reached ceiling in our preliminary study; second, the age ranges of middle-aged and older adults were continuous (53–64 and 65–81 years, respectively), while there was an age gap between middle-aged and young (20–34 years) adults. These two facts may bias the correlations between the performance in the audiovisual SJ and working memory tasks, and we therefore only conducted the CANTAB working memory tests in middle-aged and older adults.

Results

Audiovisual Simultaneity Perception

Two criteria were set in order to exclude participants who did not follow instructions, did not attend to the task, or performed as outliers in each age group. First, if the simultaneous response at the ±600 ms SOA was higher than the mean plus 2.5 standard deviation (*SD*) of that age group. Second, if the simultaneous response at the 0 ms SOA was lower than the mean minus 2.5 *SD* of that age group. Following these two criteria, five young adults, four middle-aged adults, and five older adults were excluded. Hence, there were 35 young adults, 32 middle-aged adults, and 34 older adults remaining in the final analyses (see Table 1 for the summary of demographics).

Table 1. Mean Age, Education Years, and MoCA Score, and Median of Visual Acuity (Ranges in Brackets) of Demographics and Health Status in Three Age Groups Remaining in the Final Analysis

Age group	Young	Middle-aged	Older
N	35	32	34
Female	21	27	25
Age (years)	25.6 [21–34]	60.6 [55–64]	69.2 [65–80]
Education (years)	—	13.5 [4–18]	14.8 [9–18]
MoCA score	—	28.0 [26–30]	28.3 [26–30]
Visual acuity of better eye (decimal)	1.0 [0.3–2.0]	0.9 [0.4–1.2]	0.8 [0.3–1.5]

Note: MoCA = Montreal Cognitive Assessment.

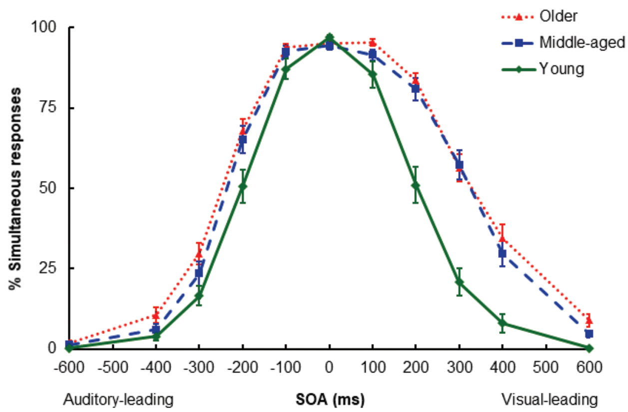

Figure 1. Mean percentage of simultaneous responses at each stimulus-onset asynchrony (SOA) for the three age groups. Error bars indicate ±1 standard error (*SE*) of the mean. Full color version is available within the online issue.

Proportion of simultaneous responses
Mean proportion of simultaneous responses of each participant at each SOA was submitted to a two-way ANOVA with a between-subject factor of age group and a within-subject factor of SOA (see Figure 1). Both main effects were significant: age group ($F(2,98) = 19.77$, $MSE = 0.11$, $p < .001$, $\eta_p^2 = 0.29$), and SOA ($F(10,980) = 602.80$, $MSE = 0.02$, $p < .001$, $\eta_p^2 = 0.86$). Critically, their interaction was also significant ($F(20,980) = 8.00$, $MSE = 0.02$, $p < .001$, $\eta_p^2 = 0.14$). Table 2 presents the results of a one-way ANOVA on the factor of age group at each SOA, and the post hoc tests at the SOAs where the simple main effect of age group was significant (paired *t* tests, two-tailed, Bonferroni corrected). The age group effect was significant at 8 out of the 11 SOAs, with exceptions at the −400, −100, and 0 ms SOAs. The age group effect arose mainly because the older adults made more simultaneous responses than young adults when the sound led the flash by 600, 300, and 200 ms, as well as when the flash led the sound by 100 ms or greater. Middle-aged adults made more simultaneous responses than young adults when the flash led the sound by 200, 300, and 400 ms (i.e., only in the visual-leading conditions).

Estimated parameters of SJ
Individual data were fitted with the Matlab routine for the SJ task (Alcalá-Quintana & García-Pérez, 2013). Eight parameters (λV, λA, τ, δ, PSS, εAF, εVF, and εS) were estimated, and each parameter was submitted to a one-way ANOVA on the factor of age group (see Table 3).

The precision of audiovisual simultaneity perception (δ) demonstrated a significant age group effect ($p < .001$). Post hoc tests revealed that δ was larger in both older and middle-aged adults than young adults (both *p*s < .001). The PSS

Table 2. Mean Percentage and Standard Error (*SE*, in Parentheses) of Simultaneous Responses in Each Age Group, and the Results of One-Way ANOVA and Post Hoc Tests for the Percentage of Simultaneous Responses (Bonferroni Corrected) at Each SOA

SOA (ms)	Young	Middle-aged	Older	$F(2,98)$	p	Post hoc tests
−600	0.3 (0.2)	1.4 (0.5)	2.1 (0.5)	5.29	< .01	Older > Young**
−400	4.0 (1.3)	6.1 (1.8)	10.6 (2.5)	3.06	= .05	
−300	16.6 (3.0)	23.6 (3.8)	29.7 (3.3)	3.89	< .05	Older > Young*
−200	50.6 (5.2)	65.2 (4.3)	68.1 (3.5)	4.67	< .05	Older > Young*
−100	87.1 (3.2)	92.7 (1.7)	93.8 (1.2)	2.58	= .08	
0	97.0 (0.8)	94.4 (1.2)	95.0 (0.9)	1.87	= .16	
100	85.4 (4.2)	91.6 (1.6)	95.4 (1.2)	3.48	< .05	Older > Young*
200	51.0 (5.6)	80.9 (3.5)	83.7 (2.2)	20.07	< .001	Older > Young**; Middle-aged > Young**
300	20.9 (4.2)	57.3 (4.6)	56.5 (4.2)	23.43	< .001	Older > Young**; Middle-aged > Young**
400	8.0 (2.9)	29.7 (4.1)	34.4 (4.5)	13.64	< .001	Older > Young**; Middle-aged > Young**
600	0.3 (0.2)	4.7 (1.2)	9.0 (2.0)	11.03	< .001	Older > Young**

Notes: ANOVA = analysis of variance; SOA = stimulus-onset asynchrony.
$^{*}p < .05$. $^{**}p < .01$.

Table 3. Mean and *SE* (in Parentheses) of Estimated Parameters of the Simultaneity Judgments Task in Each Age Group, and the Results of One-Way ANOVA as Well as Post Hoc Tests (Bonferroni Corrected)

Parameter	Young	Middle-aged	Older	$F(2,98)$	p	Post hoc tests
δ	213.1 (11.1)	283.4 (9.3)	290.3 (8.3)	19.87	< .001	Older > Young**; Middle-aged > Young**
PSS	8.2 (7.2)	42.9 (9.1)	40.5 (8.0)	5.85	< .005	Older > Young*; Middle-aged > Young**
λA	0.115 (0.047)	0.096 (0.041)	0.093 (0.041)	0.08	= .93	
λV	0.207 (0.053)	0.171 (0.042)	0.183 (0.046)	0.16	= .86	
τ	−16.8 (9.1)	−50.3 (13.7)	−53.3 (14.0)	2.72	= .07	
εAF	0.005 (0.002)	0.012 (0.004)	0.015 (0.005)	1.83	= .17	
εS	0.015 (0.006)	0.049 (0.012)	0.023 (0.006)	4.44	< .05	Middle-aged > Young*
εVF	0.006 (0.003)	0.050 (0.011)	0.086 (0.018)	10.34	< .001	Older > Young**; Middle-aged > Young*

Notes: δ = precision (threshold) of audiovisual simultaneity perception; εAF = response errors in the auditory-leading trials; εS = response errors in the simultaneous trials; εVF = response errors in the visual-leading trials; λA = processing variability of auditory stimulus; λV = processing variability of visual stimulus; PSS = point of subjective simultaneity; τ = processing time difference between visual and auditory stimulus (τA − τV).
$^{*}p < .05$. $^{**}p < .01$.

was positive (i.e., located on the visual-leading side) and significantly differed from 0 in the older ($t(33) = 5.06, p < .001$) and middle-aged ($t(31) = 4.72, p < .001$) groups, and had the same trend but not significant in the young adults ($t(34) = 1.14$, $p = .26$). Consistently, the age group effect was significant in the PSS ($p < .005$) that the PSS was located at more positive SOAs in the older and middle-aged adults as compared to the young adults (both *p*s < .05).

There was no age group effect for the three unisensory processing parameters: auditory processing variability (λA), visual processing variability (λV), and processing time difference (τ) (all *p*s ≥ .05). The τ was negative (suggesting the auditory signal arrived first at the central comparator when the two stimuli were presented simultaneously) in both older ($t(33) = -3.80, p < .005$) and middle-aged groups ($t(31) = -3.66, p < .005$), and in the same direction but not significant in the young adults group ($t(34) = -1.84, p = .07$).

In contrast, there were significant age group effects for the executive parameters in the simultaneous condition (εS) and in the visual-leading condition (εVF) (*p*s < .05). Post hoc tests revealed that the εS was higher for middle-aged than young adults ($p < .05$), and the εVF was higher for both older and middle-aged than young adults (both *p*s < .05).

Regarding the three parameters that reliably demonstrated significant differences across the three age groups, we verified that each of their correlation with age was significant when visual acuity was controlled (δ: $r = 0.55$, $p < .001$; PSS: $r = 0.34$, $p < .005$; εVF: $r = 0.44$, $p < .001$). Hence, the age-related changes of these three parameters cannot be simply explained by their current visual acuity (i.e., a peripheral sensory factor).

Correlations Between Audiovisual Simultaneity Parameters and CANTAB Performance

The CANTAB performances in the middle-aged and older groups, and the results of the *t* test (two-tailed, equal variance assumed) are reported in Supplementary Appendix B.

Table 4. Partial Correlations Between Three Parameters of Audiovisual Simultaneity Perception, and Their Correlations With the Five Behavioral Indices of the CANTAB Subtests When the Factors of Age and Visual Acuity Were Controlled

	δ	PSS	εVF	PRM RT	DMS RT	SRM RT	SWM Total errors	SSP Span length
δ	—	0.342**	0.416**	0.009	−0.039	−0.099	0.059	0.024
PSS	—	—	0.059	−0.009	−0.036	−0.111	−0.142	0.017
εVF	—	—	—	0.218	0.236	0.262*	−0.083	−0.051

Notes: δ = precision of audiovisual simultaneity perception; εVF = response errors in the visual-leading conditions; PSS = point of subjective simultaneity; RT = response time.
$^{**}p < .01$. $^{*}p < .05$, uncorrected.

We then examined whether the three parameters of audiovisual simultaneity perception that demonstrated a significant effect of age group (i.e., δ, PSS, and εVF) were correlated with each other, and whether they were correlated with the five behavioral indices of working memory performances in the middle-aged and older adults (see Table 4). Partial correlations were conducted and the factors of age and visual acuity were used as covariates in order to control for their influences.

The results demonstrated that δ was correlated with both PSS and εVF (both *p*s < .01), while the latter two were not correlated. More critically, εVF was positively correlated with the response time (RT) in the SRM task ($p < .05$, uncorrected), and in the same trend but not significant in the PRM ($p = .08$) and DMS tasks ($p = .06$). This result suggests that the middle-aged and older adults who made more response errors in the visual-leading conditions in the SJ task also took a longer time to recognize the locations of previously viewed objects (i.e., the SRM task).

Discussion

We measured the age-related changes of audiovisual simultaneity perception, and examined their relations to visual working memory in middle-aged and older adults. The results demonstrate that, compared to young adults, the older adults (>65 years old) judged a flash and beep as simultaneous more often in both auditory-leading and visual-leading conditions, while the middle-aged adults (53–64 years old) mainly did so in the visual-leading conditions. Model-fitting results demonstrate that, starting from middle age, the precision of audiovisual simultaneity perception became worse (i.e., larger δ), the PSS shifted further toward the visual-leading condition, and response errors in the visual-leading condition increased (i.e., larger εVF). More critically, the middle-aged and older participants with higher εVF responded slower in the SRM task when the factors of age and visual acuity were controlled.

Three unique results are found in the current study: First, the poorer precision of audiovisual simultaneity perception with aging started from the middle age range (cf. Basharat et al., 2018; Fiacconi et al., 2013; Stevenson et al., 2018), which is earlier than the age reported in the literature (see Baum & Stevenson, 2017; Brooks et al., 2018, for reviews). It is possible that the wider range of SOAs and a better model-fitting routine for the SJ task used in the current study leads to a more accurate estimation of the audiovisual simultaneity perception (cf. Bedard & Barnett-Cowan, 2016; Noel et al., 2016; Stevenson et al., 2018). Note that our middle-aged group (53–64 years) was older than the middle-aged group (40–59 years) in Stevenson et al. (2018). However, when we only analyzed the middle-aged participants younger than 60 years old ($N = 11$), their precision remained worse than young adults (see Supplementary Appendix C). Second, the PSS started to shift further toward the visual-leading side from the middle age range, contrasting the lack of age-related change of PSS reported in previous studies (Bedard & Barnett-Cowan, 2016; Fiacconi et al., 2013). The shift of PSS suggests that the precision became poorer more pronouncedly in the visual-leading than the auditory-leading condition with aging. Third, the εVF increased with age. This is an executive parameter associated with eye blinks, lapses of attention, and response errors in the visual-leading trials. Also, this factor correlated with the middle-aged and older adults' working memory performance in terms of the RT measure in the SRM task.

It seems reasonable to suppose that the poorer precision of audiovisual simultaneity perception with aging may be caused by sensory loss during aging (e.g., de Dieuleveult et al., 2017). Previous studies, however, have demonstrated that older adults' poorer precision of audiovisual simultaneity perception cannot be accounted for by their degeneration of detection sensitivity and temporal acuity in vision and audition (Chan et al., 2014a; Stevenson et al., 2018). Consistently, here we demonstrated that the correlation between participants' age and precision (δ) remained significant when the influence of visual acuity was controlled. An alternative account suggests that the noise in each sensory system increases with age, leading to a higher variability in information processing (Mozolic et al., 2012). However, our model-fitting results demonstrated that the visual and auditory processing variability (λV and λA, respectively) did not reveal a significant effect of age group. Combining these results therefore suggests that the poorer precision of audiovisual simultaneity perception with aging is unlikely attributed to the degeneration of unisensory systems; instead, it is more plausible that the deteriorated precision is attributed to degeneration occurring at the central comparator, which is responsible for decoding the timing of visual and auditory signals. Consistent neurophysiological evidence has revealed the reduction of the volume of superior temporal sulcus (STS) during aging (Peters, 2006), a cortical area that underpins people's subjective perception of audiovisual simultaneity (Noesselt et al., 2012; see de Dieuleveult et al., 2017, for a review).

We observed a shift of PSS toward the visual-leading condition for the middle-aged and older adults further than for the young adults; more specifically, a more pronounced deteriorated of precision in the visual-leading than in the auditory-leading condition was observed in these adults. At least three possibilities may account for this age-related change. First, Stevenson et al. (2018) demonstrated that the decline of unisensory temporal acuity occurred earlier in vision than in audition during aging. Second, Murray et al. (2018) reported that the majority of older adults demonstrated an auditory dominance in terms of faster responses to auditory signals than visual signals, in contrast to young adults with similar RT to both signals. These two accounts would both predict a longer time for visual than auditory processing. That is, a visual signal needs to be presented earlier than an auditory signal in order for them to be perceived simultaneously, leading to a shift of the PSS toward the visual-leading condition. However, in the current study, the processing time difference between the visual and auditory signal ($\tau = \tau A - \tau V$) did not significantly differ between the three age groups. Furthermore, the window of audiovisual simultaneous perception was widened in both the visual-leading and auditory-leading conditions in the older adults, rather than an overall shift toward the visual-leading condition. Therefore, neither the account of earlier degeneration of vision than audition, nor the account of auditory dominance, provides a full explanation for the shift of PSS in the middle-aged and older adults.

The third account regards the malleability of the audiovisual mechanism. Perceiving audiovisual simultaneity is challenging because of two temporal factors: In the physical world, light travels faster than sound, and this travel time difference increases as the distance between stimulus source and perceiver increases. In addition, the neural processing time from sensory receptors to the cortex is longer for vision than audition by around 30–40 ms (Vroomen & Keetels, 2010). Given that the travel time difference varies, whereas the neural processing time difference is constant, people's window of audiovisual simultaneity perception is suggested to be malleable when taking the distance of stimulus source into consideration (Engel & Dougherty, 1971; Sugita & Suzuki, 2003; see Vroomen & Keetels, 2010, for a review). Specifically, the farther the stimulus source, the earlier the arrival time of visual than auditory signal (i.e., the visual-leading condition). Previous studies have demonstrated that the visual-leading side is more malleable than auditory-leading side after training (Donohue et al., 2010; Powers et al., 2009), which is plausibly underpinned by the plasticity remaining in the audiovisual system in order to accommodate the travel time differences as a function of stimulus distances. Nevertheless, this plasticity decreases during aging (Chan et al., 2014b; Noel et al., 2016). It is possible that the middle-aged and older participants were not able to rapidly adjust their audiovisual simultaneity window to accommodate the setting in the laboratory (i.e., a close audiovisual source that the travel time difference was negligible). Hence, the pronounced degeneration of precision in the visual-leading condition may be attributed to the reduced plasticity in the aging brains, thus failing to accommodate the travel time differences of light and sound.

Regarding the three parameters of audiovisual simultaneity perception that demonstrated an age group effect (i.e., δ, PSS, and εVF), εVF was the only one correlated with middle-aged and older adult's performance in the spatial working memory task (SRM). The εVF parameter represents a participant's eye blinks, lapses of attention, and errors in responses when conducting the SJ task, which is a postperceptual factor that relates to the executive stage of information processing (see García-Pérez & Alcalá-Quintana, 2012). This executive ability should modulate people's performance when a behavioral response is needed, including the SJ task and the SRM task in the CANTAB used here. Hence, we suggest that the degeneration of executive function is a higher-order mechanism that leads to the degraded performance in both audiovisual SJ and working memory tasks. This is an evidence demonstrating that a third factor (i.e., the executive function) is the common cause determining older adults' perception and cognition, although they are not causally related (cf. Humes et al., 2013; see Roberts & Allen, 2016, for a review).

Our conclusions, nevertheless, should be reserved when considering the design of the current study due to the following reasons. First, we demonstrated that the middle-aged and older adults' performance in the audiovisual SJ task was correlated with their age when controlled for their far-distance visual acuity (5 m). However, other early visual functions (such as near-distance visual acuity and contrast sensitivity at different spatial scales), as well as early auditory functions (such as audibility curve), were not measured. It therefore remains unclear whether these other unisensory processing factors would contribute to older adults' audiovisual simultaneity perception. Second, although the working memory subtests chosen from the CANTAB are all well-developed tools, they are broad and exploratory. In future research, more specific working memory measures are required to better understand the relationships between various types of working memory functions and audiovisual simultaneity perception. Finally, the current study is cross-sectional; a longitudinal study will be better characterizing the changes of audiovisual simultaneity perception during aging.

Overall, the current study assesses the changes of audiovisual simultaneity perception across young, middle-aged, and older adults. We demonstrated that precision starts to deteriorate from middle age. More critically, such deteriorated precision was more pronounced in the visual-leading than auditory-leading condition, giving rise to a shift of the PSS further toward the visual-leading condition. We suggest that these two age-related changes are attributed to the degeneration of central mechanisms taking charge of audiovisual perception, rather than the changes in the peripheral visual or auditory processing. Finally, we demonstrated that the declined performances in the audiovisual SJ tasks and working memory tasks have a common cause at the executive stage of information processing. Therefore, training older adults' executive functions should improve their behavioral performances in general; however, individual training programs for audiovisual perception (e.g., Powers et al., 2009 in young adults) and working memory (e.g., Borella et al., 2010) are needed, and the training effect might not be transferable to each other. Our results are critical for understanding the aging brain and designing a training regime for older adults.

Supplementary Material

Supplementary data are available at *The Journals of Gerontology, Series B: Psychological Sciences and Social Sciences* online.

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Conflict of Interest

None declared.

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