The Effect of Endogenous Spatial Cue Validity on Audiovisual Integration in Older Adults

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Abstract

Audio-visual integration is the process of integrating visual and auditory information into a unified, coherent, and stable perceptual process. The study employed an endogenous cue-target paradigm to investigate the effects of different endogenous spatial cue validities on audio-visual integration in older adults, as well as the differences in audio-visual integration between older and younger adults under different cue validity conditions. The results indicated that (1) regardless of cue validity level, audio-visual integration in older adults was weaker than that in younger adults; (2) under low cue validity (50%) conditions, the audio-visual integration effects for both older and younger adults under valid cue conditions did not differ from those under invalid cue conditions; (3) under medium cue validity (70%) conditions, the audio-visual integration effect in older adults under valid cue conditions did not differ from that under invalid cue conditions, whereas in younger adults, the audio-visual integration effect under valid cue conditions was significantly higher than under invalid cue conditions; (4) under high cue validity (90%) conditions, the audio-visual integration effects for both older and younger adults under valid cue conditions were significantly higher than under invalid cue conditions. The findings support the spatial uncertainty hypothesis and further reveal the interaction between endogenous attention and audio-visual integration, clarifying that differences in endogenous spatial attentional orienting benefits under different cue validity conditions constitute one of the factors contributing to the differences in audio-visual integration between older and younger adults.

Full Text

Effects of Endogenous Spatial Cue Validity on Audiovisual Integration in Older Adults

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Abstract

Audiovisual integration is the process of integrating visual and auditory information into a unified, coherent, and stable percept. This study employed an endogenous cue-target paradigm to investigate how different levels of endogenous spatial cue validity affect audiovisual integration in older adults, as well as the differences in audiovisual integration between older and younger adults under varying cue validity conditions. The results indicated that: (1) regardless of cue validity level, older adults exhibited weaker audiovisual integration than younger adults; (2) under low cue validity (50%), audiovisual integration effects did not differ between valid and invalid cue conditions for either older or younger adults; (3) under medium cue validity (70%), older adults showed no difference in audiovisual integration between valid and invalid cue conditions, whereas younger adults demonstrated significantly stronger audiovisual integration under valid compared to invalid cue conditions; and (4) under high cue validity (90%), both older and younger adults exhibited significantly stronger audiovisual integration under valid versus invalid cue conditions. These findings support the spatial uncertainty hypothesis and further reveal the interactive relationship between endogenous attention and audiovisual integration, clarifying that differences in endogenous spatial attentional orienting benefits under varying cue validity conditions contribute to the observed differences in audiovisual integration between older and younger adults.

Keywords: endogenous spatial attention, audiovisual integration, older adults, cue validity

Vision and audition are critical sensory channels through which humans obtain information in daily life. When visual and auditory stimuli co-occur and refer to the same event, they are perceived as a coherent stimulus—a perceptual process known as audiovisual integration (Talsma & Woldorff, 2005; 唐晓雨 et al., 2020). Compared to unimodal visual or auditory stimuli, integrated audiovisual stimuli are identified more quickly and accurately, a phenomenon referred to as the redundancy effect (Gao et al., 2014; Li et al., 2010; Wu et al., 2012). Previous research has demonstrated that audiovisual integration is influenced not only by bottom-up factors such as temporal and spatial congruency between audiovisual stimuli (Fleming et al., 2020; Li et al., 2015), but also by top-down factors such as endogenous attention (Talsma & Woldorff, 2005; Tang et al., 2016). Among these, a particularly important mechanism is the influence of endogenous spatial attention on audiovisual integration (Talsma & Woldorff, 2005; 唐晓雨 et al., 2020).

Endogenous spatial attention refers to the conscious monitoring of stimulus signals at a specific location and represents a top-down form of attention (Posner, 1980). Existing studies have employed the endogenous cue-target paradigm, using symbolic cues to guide participants to focus attention on a spatial location while manipulating attentional allocation through variations in cue validity proportions. If participants' response times under valid cue conditions are significantly faster than under invalid cue conditions, this indicates a cueing effect, suggesting that endogenous spatial attention has been successfully oriented (Arjona et al., 2016; Vossel et al., 2006). Regarding the influence of endogenous spatial attention on audiovisual integration, Donohue et al. (2015) found that when cue validity was 75%, participants demonstrated higher accuracy in identifying audiovisual stimuli under valid cue conditions. Similarly, 唐晓雨 et al. (2020) reported that at 80% cue validity, audiovisual integration effects were stronger under valid compared to invalid cue conditions, indicating that endogenous spatial attention facilitates audiovisual integration. Additionally, Talsma and Woldorff (2005) induced endogenous spatial attention through instructions and likewise found enhanced audiovisual integration effects at attended locations. In summary, studies manipulating endogenous spatial attention through various methods have consistently found that it promotes audiovisual integration (Donohue et al., 2015; Talsma et al., 2010; Talsma & Woldorff, 2005; 唐晓雨 et al., 2020). However, these studies have exclusively examined young adults aged 18-26, leaving unclear how endogenous spatial attention affects audiovisual integration in older adults.

Evidence suggests that endogenous spatial attention in older adults gradually declines with age (Erel & Levy, 2016; Juola et al., 2000; Zivony et al., 2019). Previous research using the endogenous cue-target paradigm to investigate spatial attention orienting in older adults has revealed this decline in two ways. First, older adults exhibit weaker endogenous attentional orienting benefits than younger adults, indicating less efficient cue utilization (Erel & Levy, 2016; Slessor et al., 2016; Zivony et al., 2019). Second, older adults show significantly higher error rates and longer response times under invalid cue conditions, suggesting reduced flexibility in attentional shifting and weaker inhibition of irrelevant stimuli compared to younger adults (Juola et al., 2000). Furthermore, functional magnetic resonance imaging (fMRI) studies have found that gray matter volume in the prefrontal cortex decreases with age (DeCarli et al., 2005; Lockhart & DeCarli, 2014), and Erel and Levy (2016) have suggested that this reduction is associated with the decline in endogenous spatial attention in older adults. These studies collectively confirm that endogenous spatial attention differs between older and younger adults. Additionally, research has found that older adults' perceptual sensitivity to visual and auditory stimuli is significantly weaker than that of younger adults (Parada et al., 2021; Tremblay et al., 2021), and their audiovisual integration also differs from younger adults (Jones

& Noppeney, 2021; Yang et al., 2021). Some studies have reported stronger audiovisual integration effects in older adults (Laurienti et al., 2006; Peiffer et al., 2007). For example, Laurienti et al. (2006) found that when stimuli were presented centrally, older adults showed stronger audiovisual integration effects, attributing this to the inverse effectiveness principle in audiovisual integration—whereby weaker unimodal stimulus intensity facilitates integration. Since older adults have reduced visual and auditory sensitivity, their audiovisual integration is enhanced (Laurienti et al., 2006). However, other studies have found that audiovisual integration is weaker in older adults (Ren et al., 2021; Stephen et al., 2010; Wu et al., 2012; Yang et al., 2021). Researchers attribute these discrepancies to stimulus location, proposing that when stimuli appear in the periphery, older adults' slower processing of peripheral stimuli reduces the probability of audiovisual integration (Diederich et al., 2008; Wu et al., 2012). Although debate continues regarding whether audiovisual integration is stronger or weaker in older adults, existing evidence consistently indicates that audiovisual integration differs between older and younger adults (Yang et al., 2021).

In summary, while previous research on audiovisual integration in older adults has examined factors such as perceptual sensitivity and stimulus location, it has not addressed the influence of endogenous spatial attention. Moreover, although endogenous spatial attention is known to facilitate audiovisual integration in younger adults, research has also established age-related differences in endogenous spatial attention. It remains unclear how endogenous spatial attention affects audiovisual integration in older adults and how audiovisual integration differs between older and younger adults under endogenous spatial attention conditions. Therefore, this study employed the endogenous cue-target paradigm, with participant type (younger vs. older adults), cue type (valid vs. invalid cues), and target stimulus type (visual vs. auditory vs. audiovisual stimuli) as independent variables. Through three experiments, we examined the effects of endogenous spatial attention on audiovisual integration in older adults under three cue validity conditions: 50% (Experiment 1), 70% (Experiment 2), and 90% (Experiment 3). We selected three different cue validity levels to manipulate endogenous spatial attention because previous research has shown that cue validity modulates the allocation of endogenous spatial attention, with higher cue validity producing larger cueing effects (Arjona et al., 2016). Additionally, 唐晓雨 et al. (2020) found that endogenous spatial attention differentially affects audiovisual integration in younger adults depending on cue validity: at 80% cue validity, endogenous spatial attention promoted audiovisual integration, whereas at 50% cue validity, it did not. van der Stoep et al. (2015) proposed the "spatial uncertainty hypothesis," which posits that because valid cues and target stimuli provide redundant spatial orienting information, lower cue validity increases uncertainty about target location, causing participants to rely more heavily on cue information for spatial orienting. Consequently, the importance of audiovisual target stimuli decreases (van der Stoep et al., 2015), and they receive fewer attentional resources (唐晓雨 et al., 2020). Based on this, we hypothesized that under 50% cue validity, the reduced attentional resources allocated to target stimuli would prevent endogenous spatial attention from promoting audiovisual integration in either older or younger adults. Furthermore, given that endogenous spatial attention is weaker in older adults (Olk & Kingstone, 2009) and that older adults exhibit lower attentional orienting benefits (Slessor et al., 2016; Zivony et al., 2019), we hypothesized that higher cue validity would be necessary for endogenous spatial attention to promote audiovisual integration in older adults, whereas lower cue validity would not facilitate audiovisual integration in this population. Additionally, because older adults have weaker discrimination abilities for peripheral stimuli (Anderson & McDowell, 1997), we predicted that older adults would show weaker audiovisual integration than younger adults across all cue validity conditions.

Experiment 1

2.1.1 Participants

Based on the effect size ($p^2 = 0.307$) from Ren et al. (2018) examining age differences in audiovisual integration effects, and the desired power of 0.80 from Ren et al. (2018) and 唐晓雨 et al. (2020), we used G*Power 3.1.9 software to calculate the required sample size. With effect size f set to 0.307, power ($1-\beta$) at 80%, and α level at 0.05, the calculated sample size was 24 participants per group.

Experiment 1 recruited 25 older adults (18 males, 7 females) from a senior university with a mean age of 64.1 ± 4.9 years, and 26 university students (15 males, 11 females) with a mean age of 22.6 ± 2.4 years. All participants had normal or corrected-to-normal vision, normal hearing, good health, and no brain injury. None had prior experience with similar experiments. Data from one older adult and one younger adult were excluded due to accuracy rates below 90%, and data from one younger adult were excluded because the minimum number of valid trials in a single condition fell below 70% of the total trials for that condition. A sensitivity analysis for independent-samples t-tests was conducted using G*Power 3.1.9, with $\alpha = 0.05$ and power = 0.80, yielding an effect size dz = 0.83 for Experiment 1, indicating adequate statistical power with a large effect size.

2.1.2 Apparatus and Materials

All stimuli were presented on a 14-inch Intel(R) Graphics 620 monitor with a resolution of 1024 × 768 and a refresh rate of 60 Hz. Participants were seated 50 cm from the screen center. The experimental program was compiled using E-Prime 1.1, and all stimuli were presented on a black background (RGB: 0, 0, 0). The fixation display consisted of three horizontally arranged gray-white boxes (RGB: 127, 127, 127) and a central fixation point. Each gray-white box measured 4.4° × 4.4°, with a plus-shaped fixation point "+" (0.5° × 0.5°) in the central box. The distance between the central fixation point and the peripheral boxes was 11°. Target stimuli included three types: visual (V), auditory (A), and audiovisual (AV). The visual stimulus was a 2° × 2° red (RGB: 234, 86, 97) and yellow (RGB: 247, 200, 125) intersecting meta-pattern presented in either the left or right box. The auditory stimulus was a 1600 Hz, 60 dB pure tone presented through binaural earphones (Realme RMA-155). The audiovisual stimulus consisted of visual and auditory stimuli presented simultaneously on the same side. Stimulus duration was 100 ms. The experimental stimuli are illustrated in Figure 1a [Figure 1: see original paper].

The experiment employed a mixed 2 (participant type: older vs. younger adults) × 2 (cue type: valid vs. invalid cue) × 3 (target stimulus type: visual vs. auditory vs. audiovisual) design. Participant type was a between-subjects variable, while cue type and target stimulus type were within-subjects variables. The dependent variables were accuracy and response time.

2.1.3 Procedure

The trial sequence is shown in Figure 1b. The fixation display was presented for 500 ms, followed by the cue display for 200 ms. The cue was an arrow pointing left or right. After a 600 ms inter-stimulus interval, the target stimulus (visual, auditory, or audiovisual) appeared in either the left or right box for 100 ms. Participants were informed that cue validity was 50% and were instructed to judge the location of the target stimulus, pressing the "N" key when it appeared on the left and the "M" key when it appeared on the right. Each participant completed 480 experimental trials (240 valid cue trials; 240 invalid cue trials) divided into 4 blocks of 120 trials each, with trial types randomly intermixed. Participants rested for 1 minute between blocks. Twenty practice trials preceded the formal experiment. The experiment lasted approximately 20 minutes.

Figure 1. (a) Example of experimental stimuli, showing the size and location of target presentation; (b) Experimental trial sequence. Note: Target stimuli (A/V/AV) represent auditory, visual, and audiovisual stimuli, respectively. ISI (inter-stimulus interval) is the interval between cue and target. ITI (inter-trial interval) is the interval between trials.

2.1.4 Data Analysis

This study used relative amount of multisensory response enhancement (rMRE) and the race model inequality to analyze audiovisual integration effects (唐晓雨 et al., 2020; Miller, 1982).

The rMRE was calculated using the median response time for each target stimulus condition, employing formula (a) to compute the relative difference between the minimum of visual and auditory response times and the audiovisual response time. This yields the relative increase or decrease in audiovisual response time. The resulting values were then subjected to one-sample t-tests (compared against 0). If results were significantly greater than 0, audiovisual integration was considered to have occurred.

$$\frac{\mathrm{Min}(\mathrm{median}(RT_A), \mathrm{median}(RT_V)) - \mathrm{median}(RT_{AV})}{\mathrm{Min}(\mathrm{median}(RT_A), \mathrm{median}(RT_V))} \times 100\% \quad \text{(a)}$$

The race model inequality uses the cumulative distribution functions (CDFs) of visual and auditory response times to calculate the race model, as shown in formula (b). $P(RT_A < t)$ represents the response probability for auditory stimuli at a given time t, while $P(RT_V < t)$ represents the response probability for visual stimuli at time t. Formula (b) calculates the cumulative distribution function formed by visual and auditory response times, $P(RT_{\text{Race model}} < t)$, which is then compared to the actual audiovisual response time CDF, $P(RT_{AV} < t)$. The difference between these CDFs yields the probability difference at each 10 ms interval within the response time range (100-1200 ms in this study). When the actual audiovisual response time CDF is significantly greater than the race model CDF during a specific time window, audiovisual integration is considered to have occurred within that window. By comparing whether audiovisual integration time windows emerge across conditions and whether peak percentage magnitudes differ when windows are present, we can determine whether audiovisual integration magnitude differs between conditions (Hugenschmidt et al., 2009; Yang & Ren, 2018).

$$P(RT_{\text{Race model}} < t) = P(RT_A < t) + P(RT_V < t) \quad \text{(b)}$$

2.2 Results and Analysis

Trials with response times less than 100 ms or greater than 1200 ms were excluded as outliers. As shown in Table 1 , the final average number of valid trials was 228 for older adults under valid cues and 228 under invalid cues; for younger adults, it was 230 under valid cues and 227 under invalid cues.

Table 1 Mean number of valid trials across experimental conditions

Condition	Older Adults	Younger Adults
Valid Cue	228 (240)	230 (240)
Invalid Cue	228 (240)	227 (240)

Note: Numbers in parentheses represent total trials per condition.

Overall accuracy rates are presented in Table 2 . Both older and younger adults achieved high accuracy across conditions, so only response times were analyzed.

Table 2 Accuracy (ACC/%) and response time (RT/ms) (M ± SD) in Experiment 1

Target Type	Valid Cue (Older)	Invalid Cue (Older)	Valid Cue (Younger)	Invalid Cue (Younger)
Visual	97.6 ± 2.8	98.4 ± 1.8	98.9 ± 1.3	97.7 ± 2.4
Auditory	98.0 ± 2.0	92.4 ± 4.3	96.1 ± 3.8	94.1 ± 5.0
Audiovisual	97.7 ± 2.5	97.6 ± 2.5	98.8 ± 2.1	97.9 ± 2.7
Visual RT	440 ± 173	455 ± 174	338 ± 76	347 ± 75
Auditory RT	433 ± 149	448 ± 143	364 ± 97	396 ± 99
Audiovisual RT	375 ± 161	392 ± 162	280 ± 61	300 ± 79

Note: ACC = Accuracy (%), RT = Reaction time (ms)

2.2.1 Response Times A 2 (participant type: younger vs. older adults) × 2 (cue type: valid vs. invalid cue) × 3 (target stimulus type: visual vs. auditory vs. audiovisual) repeated-measures ANOVA was conducted on response times from correct trials. Results are shown in Table 2. The main effect of participant type was significant, $F(1, 46) = 5.88$, $p = 0.019$, $\eta_p^2 = 0.11$, with younger adults responding significantly faster (338 ms) than older adults (424 ms). The main effect of cue type was significant, $F(1, 46) = 33.10$, $p < 0.001$, $\eta_p^2 = 0.42$, with faster responses under valid cues (372 ms) than invalid cues (390 ms). The main effect of target stimulus type was significant, $F(2, 92) = 58.59$, $p < 0.001$, $\eta_p^2 = 0.56$. Multiple comparisons revealed that audiovisual stimuli were responded to significantly faster (337 ms) than visual stimuli (395 ms), $t(47) = 8.11$, $p < 0.001$, $d = 0.45$, 95% CI = [40.65, 75.55], and auditory stimuli (410 ms), $t(47) = 10.26$, $p < 0.001$, $d = 0.58$, 95% CI = [56.02, 90.94]. The interaction between participant type and target stimulus type was significant, $F(2, 92) = 5.09$, $p = 0.008$, $\eta_p^2 = 0.10$. No other interactions were significant, $ps > 0.05$.

Additionally, one-sample t-tests on cueing effects (Cue effect = RT_{invalid} - RT_{valid}) for both older and younger adults yielded results significantly greater than 0, $ps < 0.05$, $ds > 0.59$, confirming that both age groups exhibited endogenous spatial attention. Given the baseline differences in response times between older and younger adults, we first normalized the response time data using formula (c) (X = raw data, M = mean, SD = standard deviation), then conducted independent-samples t-tests on the normalized cueing effects for visual, auditory, and audiovisual conditions. No significant differences emerged between older and younger adults, $ts(46) < 1.72$, $ps > 0.05$.

$$\frac{X - M}{SD} \quad \text{(c)}$$

2.2.2 Relative Multisensory Response Enhancement (rMRE) First, rMRE values were calculated from median response times for each condition. One-sample t-tests (against 0) were then conducted on rMRE values for each participant type and cue type. Results showed that rMRE values were significantly greater than 0 for older adults across cue types, $ts(23) > 4.28$, $ps < 0.001$, $ds > 0.87$, and for younger adults across cue types, $ts(23) > 3.73$, $ps < 0.05$, $ds > 0.76$. These findings indicate that both older and younger adults exhibited audiovisual integration effects across all cue type conditions.

Second, paired-samples t-tests comparing rMRE between valid and invalid cue conditions revealed no significant difference for older adults, $t(23) = 0.68$, $p > 0.05$. Similarly, for younger adults, no significant difference emerged between valid and invalid cue conditions, $t(23) = 1.03$, $p > 0.05$.

Finally, independent-samples t-tests were conducted on rMRE values for each participant type under valid and invalid cue conditions to examine age-related differences in audiovisual integration. As shown in Figure 2 Figure 2: see original paper, under valid cue conditions, younger adults' rMRE (14.1%) was significantly greater than older adults'rMRE (8.6%), $t(46) = 2.27$, $p = 0.028$, $d = 0.65$, 95% CI = [0.62, 10.50]. Under invalid cue conditions, the difference between younger and older adults' rMRE was not significant, $t(46) = 0.42$, $p > 0.05$.

2.2.3 Race Model Analysis First, cumulative probability values were calculated at 10 ms intervals from 0-1200 ms for auditory $P(RT_A < t)$, audiovisual $P(RT_{AV} < t)$, and visual $P(RT_V < t)$ responses for both older and younger adults under each cue type condition. The cumulative probability difference between the race model CDF $P(RT_{\text{Race model}} < t)$ and the audiovisual CDF $P(RT_{AV} < t)$ was then computed. Following Nardini et al. (2016), one-tailed one-sample t-tests were conducted at each 10 ms interval.

Results for older adults are shown in Figure 3 Figure 3: see original paper and (b): Under valid cue conditions, the time window showing significant race model violation was 100 ms (190–290 ms), $ts(23) > 2.24$, $ps < 0.05$, $ds > 0.46$, with a peak at 260 ms of 4.92%. Under invalid cue conditions, the significant violation window was also 100 ms (190–290 ms), $ts(23) > 1.75$, $ps < 0.05$, $ds > 0.36$, with a peak at 270 ms of 5.64%. A paired-samples t-test comparing peaks between valid and invalid cue conditions showed no difference, $t(23) = 0.40$, $p > 0.05$. Thus, older adults showed similar onset times and time windows for race model violations across cue conditions, with no difference in peak magnitude, indicating comparable audiovisual integration effects under valid and invalid cue conditions.

Results for younger adults are shown in Figure 3(c) and (d): Under valid cue conditions, the significant race model violation window was 130 ms (110–240 ms), $ts(23) > 1.75$, $ps < 0.05$, $ds > 0.36$, with a peak at 230 ms of 4.69%. Under invalid cue conditions, the violation window was 70 ms (170–240 ms), $ts(23) > 2.31$, $ps < 0.05$, $ds > 0.47$, with a peak at 230 ms of 4.75%. A paired-samples t-test comparing peaks showed no difference, $t(23) = 0.025$, $p > 0.05$. Although younger adults showed slightly earlier onset and longer violation windows under valid versus invalid cue conditions, the absence of peak differences indicates that audiovisual integration effects did not differ between cue conditions for younger adults.

Experiment 2

The planned sample size calculation method and results were identical to Experiment 1. Experiment 2 recruited 26 older adults (16 males, 10 females) from a senior university with a mean age of 64.8 ± 5.7 years, and 28 university students (16 males, 12 females) with a mean age of 22.3 ± 2.4 years. All participants had normal or corrected-to-normal vision, normal hearing, good health, and no brain injury, with no prior experience in similar experiments. Data from two older adults and two younger adults were excluded due to accuracy rates below 90%, and data from one younger adult were excluded because the minimum number of valid trials in a single condition fell below 70% of total trials for that condition. A sensitivity analysis for independent-samples t-tests using G*Power 3.1.9 with $\alpha = 0.05$ and power = 0.80 yielded an effect size dz = 0.82 for Experiment 2, indicating adequate statistical power with a large effect size.

Experiment 2 increased cue validity to 70% while keeping all other conditions identical to Experiment 1. Each participant completed 900 experimental trials (630 valid cue trials; 270 invalid cue trials) divided into 5 blocks of 180 trials each, with trial types randomly intermixed. Participants rested for 1 minute between blocks. Thirty practice trials preceded the formal experiment, which lasted approximately 40 minutes. The experimental procedure was identical to Experiment 1.

3.2 Results and Analysis

Trials with response times less than 100 ms or greater than 1200 ms were excluded. As shown in Table 1, the final average number of valid trials was 596 for older adults under valid cues and 253 under invalid cues; for younger adults, it was 578 under valid cues and 253 under invalid cues.

Overall accuracy rates are presented in Table 3 . Both older and younger adults achieved high accuracy across conditions, so only response times were analyzed.

Table 3 Accuracy (ACC/%) and response time (RT/ms) (M ± SD) in Experiment 2

Target Type	Valid Cue (Older)	Invalid Cue (Older)	Valid Cue (Younger)	Invalid Cue (Younger)
Visual	97.6 ± 2.5	98.5 ± 1.8	98.7 ± 1.4	97.3 ± 3.1
Auditory	97.3 ± 2.7	95.1 ± 4.1	96.1 ± 3.3	90.0 ± 4.7
Audiovisual	96.6 ± 3.7	96.1 ± 3.1	98.7 ± 1.4	97.3 ± 2.4

Target Type	Valid Cue (Older)	Invalid Cue (Older)	Valid Cue (Younger)	Invalid Cue (Younger)
Visual RT	488 ± 179	535 ± 157	359 ± 123	378 ± 119
Auditory RT	451 ± 180	514 ± 146	378 ± 161	421 ± 143
Audiovisual RT	403 ± 179	463 ± 156	287 ± 107	322 ± 92

3.2.1 Response Times A 2 (participant type: younger vs. older adults) × 2 (cue type: valid vs. invalid cue) × 3 (target stimulus type: visual vs. auditory vs. audiovisual) repeated-measures ANOVA was conducted on response times from correct trials. The main effect of participant type was significant, $F(1, 47) = 8.73$, $p = 0.005$, $\eta_p^2 = 0.16$, with younger adults responding significantly faster (358 ms) than older adults (475 ms). The main effect of cue type was significant, $F(1, 47) = 30.83$, $p < 0.001$, $\eta_p^2 = 0.40$, with faster responses under valid cues (394 ms) than invalid cues (439 ms). The main effect of target stimulus type was significant, $F(2, 94) = 41.90$, $p < 0.001$, $\eta_p^2 = 0.47$. Multiple comparisons revealed that audiovisual stimuli were responded to significantly faster (369 ms) than visual stimuli (442 ms), $t(48) = 7.87$, $p < 0.001$, $d = 0.48$, 95% CI = [49.11, 93.22], and auditory stimuli (441 ms), $t(48) = 7.99$, $p < 0.001$, $d = 0.49$, 95% CI = [50.24, 94.35]. The interaction between participant type and target stimulus type was significant, $F(2, 94) = 5.97$, $p = 0.004$, $\eta_p^2 = 0.11$. The interaction between cue type and target stimulus type was also significant, $F(2, 94) = 13.23$, $p < 0.001$, $\eta_p^2 = 0.22$. No other interactions were significant, $ps > 0.05$.

One-sample t-tests on cueing effects for both older and younger adults yielded results significantly greater than 0, $ps < 0.05$, $ds > 0.64$, confirming that both age groups exhibited endogenous spatial attention. Independent-samples t-tests on normalized cueing effects for visual, auditory, and audiovisual conditions revealed no significant differences between older and younger adults, $ts(47) < 1.30$, $ps > 0.05$.

3.2.2 Relative Multisensory Response Enhancement (rMRE) First, rMRE values were calculated from median response times for each condition. One-sample t-tests (against 0) showed that rMRE values were significantly greater than 0 for older adults across cue types, $ts(23) > 5.40$, $ps < 0.001$, $ds > 1.10$, and for younger adults across cue types, $ts(24) > 4.01$, $ps < 0.001$, $ds > 0.80$. These results indicate that both older and younger adults exhibited audiovisual integration effects across all cue type conditions.

Second, paired-samples t-tests comparing rMRE between valid and invalid cue conditions showed no significant difference for older adults, $t(23) = 1.27$, $p > 0.05$. However, for younger adults, rMRE under valid cues (14.2%) was significantly greater than under invalid cues (10.0%), $t(24) = 3.03$, $p = 0.006$, $d = 0.61$, 95% CI = [1.36, 7.18].

Finally, independent-samples t-tests were conducted on rMRE values for each participant type under valid and invalid cue conditions. As shown in Figure 2(b), under valid cue conditions, younger adults' rMRE (14.2%) was significantly greater than older adults' rMRE (8.0%), $t(47) = 2.24$, $p = 0.03$, $d = 0.64$, 95% CI = [0.62, 11.77]. Under invalid cue conditions, no difference emerged between younger and older adults' rMRE, $t(47) = 1.13$, $p > 0.05$.

3.2.3 Race Model Analysis First, cumulative probability values were calculated at 10 ms intervals from 100-1200 ms for auditory $P(RT_A < t)$, audiovisual $P(RT_{AV} < t)$, and visual $P(RT_V < t)$ responses for both older and younger adults under each cue type condition. The cumulative probability difference between the race model CDF $P(RT_{\text{Race model}} < t)$ and the audiovisual CDF $P(RT_{AV} < t)$ was then computed, with one-tailed one-sample t-tests conducted at each 10 ms interval following Nardini et al. (2016).

Results for older adults are shown in Figure 4 Figure 4: see original paper and (b): Under valid cue conditions, the significant race model violation window was 30 ms (170-200 ms), $ts(23) > 2.11$, $ps < 0.05$, $ds > 0.43$, with a peak at 190 ms of 1.95%. Under invalid cue conditions, the violation window was 70 ms (140-170 ms; 290-330 ms), $ts(23) > 1.72$, $ps < 0.05$, $ds > 0.35$, with a peak at 300 ms of 3.26%. A paired-samples t-test comparing peaks showed no difference, $t(23) = 0.69$, $p > 0.05$. Thus, although older adults showed slightly later onset and smaller violation windows under valid versus invalid cue conditions, the absence of peak differences indicates comparable audiovisual integration effects across cue conditions.

Results for younger adults are shown in Figure 4(c) and (d): Under valid cue conditions, the significant race model violation window was 90 ms (130-220 ms), $ts(24) > 1.86$, $ps < 0.05$, $ds > 0.37$, with a peak at 200 ms of 4.11%. Under invalid cue conditions, the violation window was 10 ms (120-130 ms), $t(24) = 1.78$, $p = 0.04$, $d = 0.48$, with a peak at 130 ms of 0.49%. A paired-samples t-test comparing peaks revealed that the peak under valid cues (4.11%) was significantly greater than under invalid cues (0.49%), $t(24) = 2.41$, $p = 0.012$, $d = 0.48$, 95% CI = [0.129, +∞]. Thus, younger adults showed larger violation windows and higher peaks under valid versus invalid cue conditions, indicating stronger audiovisual integration effects under valid cue conditions.

Experiment 3

The planned sample size calculation method and results were identical to Experiment 1. Experiment 3 recruited 29 older adults (11 males, 18 females) from a senior university with a mean age of 70.0 ± 6.7 years, and 29 university students (8 males, 21 females) with a mean age of 21 ± 2 years. All participants had normal or corrected-to-normal vision, normal hearing, good health, and no brain injury, with no prior experience in similar experiments. Data from one older adult and two younger adults were excluded due to accuracy rates below 90%. A sensitivity analysis for independent-samples t-tests using G*Power 3.1.9 with $\alpha = 0.05$ and power = 0.80 yielded an effect size dz = 0.77 for Experiment 3, indicating adequate statistical power with a large effect size.

Experiment 3 increased cue validity to 90% while keeping all other conditions identical to Experiment 1. Each participant completed 1200 experimental trials (1080 valid cue trials; 120 invalid cue trials) divided into 10 blocks of 120 trials each, with trial types randomly intermixed. Participants rested for 1 minute between blocks. Thirty practice trials preceded the formal experiment, which lasted approximately 70 minutes. The experimental procedure was identical to Experiment 1.

4.2 Results and Analysis

Trials with response times less than 100 ms or greater than 1200 ms were excluded. As shown in Table 1, the final average number of valid trials was 1015 for older adults under valid cues and 109 under invalid cues; for younger adults, it was 1059 under valid cues and 118 under invalid cues.

Overall accuracy rates are presented in Table 4 . Both older and younger adults achieved high accuracy across conditions, so only response times were analyzed.

Table 4 Accuracy (ACC/%) and response time (RT/ms) (M ± SD) in Experiment 3

Target Type	Valid Cue (Older)	Invalid Cue (Older)	Valid Cue (Younger)	Invalid Cue (Younger)
Visual	97.9 ± 2.5	99.8 ± 0.4	99.4 ± 0.6	96.1 ± 4.4
Auditory	98.6 ± 4.4	95.4 ± 4.4	99.2 ± 1.4	90.0 ± 8.3
Audiovisual	96.6 ± 2.6	90.6 ± 7.7	97.9 ± 2.1	96.6 ± 2.6
Visual RT	446 ± 110	546 ± 112	359 ± 94	478 ± 104
Auditory RT	404 ± 95	530 ± 103	237 ± 71	322 ± 92
Audiovisual RT	358 ± 94	477 ± 104	302 ± 74	372 ± 97

4.2.1 Response Times A 2 (participant type: younger vs. older adults) × 2 (cue type: valid vs. invalid cue) × 3 (target stimulus type: visual vs. auditory vs. audiovisual) repeated-measures ANOVA was conducted on response times from correct trials. The main effect of participant type was significant, $F(1, 53) = 38.69$, $p < 0.001$, $\eta_p^2 = 0.42$, with younger adults responding significantly faster (327 ms) than older adults (460 ms). The main effect of cue type was significant, $F(1, 53) = 70.78$, $p < 0.001$, $\eta_p^2 = 0.57$, with faster responses under valid cues (341 ms) than invalid cues (446 ms). The main effect of target stimulus type was significant, $F(2, 106) = 67.08$, $p < 0.001$, $\eta_p^2 = 0.56$. Multiple comparisons revealed that audiovisual stimuli were responded to significantly faster (349 ms) than visual stimuli (417 ms), $t(54) = 10.12$, $p < 0.001$, $d = 0.70$, 95% CI = [51.41, 83.95], and auditory stimuli (416 ms), $t(54) = 10.05$, $p < 0.001$, $d = 0.69$, 95% CI = [50.96, 83.50]. The three-way interaction between participant type, cue type, and target stimulus type was significant, $F(2, 106) = 6.44$, $p = 0.002$, $\eta_p^2 = 0.11$.

To further explore the potential interaction between cue type and target stimulus type within each age group, separate 2 (cue type: valid vs. invalid) × 3 (target stimulus type: visual vs. auditory vs. audiovisual) repeated-measures ANOVAs were conducted for older and younger adults. For older adults, the interaction between cue type and target stimulus type was significant, $F(2, 54) = 5.04$, $p = 0.01$, $\eta_p^2 = 0.16$. Simple effects analysis revealed that under valid cue conditions, response times differed significantly across target stimulus types, $F(2, 54) = 41.96$, $p < 0.001$, $\eta_p^2 = 0.61$. Multiple comparisons showed that audiovisual stimuli were responded to significantly faster (358 ms) than visual stimuli (446 ms), $t(27) = 7.26$, $p < 0.001$, $d = 0.85$, 95% CI = [50.93, 124.31], and auditory stimuli (404 ms), $t(27) = 3.75$, $p < 0.001$, $d = 0.438$, 95% CI = [8.60, 81.98], with auditory stimuli also faster than visual stimuli, $t(27) = 3.58$, $p = 0.012$, 95% CI = [5.64, 79.02]. Under invalid cue conditions, response times also differed significantly across target stimulus types, $F(2, 54) = 12.66$, $p < 0.001$, $\eta_p^2 = 0.32$. Multiple comparisons showed that audiovisual stimuli were responded to significantly faster (477 ms) than visual stimuli (545 ms), $t(27) = 5.64$, $p < 0.001$, $d = 0.66$, 95% CI = [31.34, 104.72], and auditory stimuli (530 ms), $t(27) = 4.31$, $p < 0.001$, $d = 0.50$, 95% CI = [15.28, 88.67].

For younger adults, the interaction between cue type and target stimulus type was also significant, $F(2, 52) = 33.50$, $p < 0.001$, $\eta_p^2 = 0.56$. Simple effects analysis revealed that under valid cue conditions, response times differed significantly across target stimulus types, $F(2, 52) = 88.04$, $p < 0.001$, $\eta_p^2 = 0.72$. Multiple comparisons showed that audiovisual stimuli were responded to significantly faster (237 ms) than visual stimuli (301 ms), $t(26) = 8.23$, $p < 0.001$, $d = 0.72$, 95% CI = [40.90, 88.43], and auditory stimuli (292 ms), $t(26) = 7.74$, $p < 0.001$, $d = 0.67$, 95% CI = [37.04, 84.56]. Under invalid cue conditions, response times also differed significantly across target stimulus types, $F(2, 52) = 60.23$, $p < 0.001$, $\eta_p^2 = 0.70$. Multiple comparisons showed that audiovisual stimuli were responded to significantly faster (322 ms) than visual stimuli (372 ms), $t(26) = 6.31$, $p < 0.001$, $d = 0.55$, 95% CI = [25.84, 73.36], and auditory stimuli (429 ms), $t(26) = 13.51$, $p < 0.001$, $d = 1.17$, 95% CI = [82.37, 129.90], with visual stimuli also faster than auditory stimuli, $t(26) = 7.19$, $p < 0.001$, $d = 0.67$, 95% CI = [25.84, 73.36].

One-sample t-tests on cueing effects for both older and younger adults yielded results significantly greater than 0, $ps < 0.05$, $ds > 0.82$, confirming that both age groups exhibited endogenous spatial attention. Independent-samples t-tests on normalized cueing effects revealed that older adults showed significantly greater cueing effects than younger adults for visual stimuli (0.05 vs. 0.02), $t(53) = 2.16$, $p = 0.035$, $d = 0.58$, 95% CI = [0.002, 0.059], and auditory stimuli (0.06 vs. 0.004), $t(53) = 3.81$, $p < 0.001$, $d = 1.03$, 95% CI = [0.025, 0.079]. No difference emerged for audiovisual stimuli, $t(53) = 0.76$, $p > 0.05$.

4.2.2 Relative Multisensory Response Enhancement (rMRE) First, rMRE values were calculated from median response times for each condition. One-sample t-tests (against 0) showed that rMRE values were significantly greater than 0 for older adults across cue types, $ts(28) > 4.70$, $ps < 0.001$, $ds > 0.82$, and for younger adults across cue types, $ts(26) > 8.96$, $ps < 0.001$, $ds > 1.72$. These results indicate that both older and younger adults exhibited audiovisual integration effects across all cue type conditions.

Second, paired-samples t-tests comparing rMRE between valid and invalid cue conditions revealed that older adults' rMRE under valid cues (7.9%) was significantly greater than under invalid cues (5.2%), $t(27) = 2.77$, $p = 0.01$, $d = 0.52$, 95% CI = [0.71, 4.76]. Similarly, younger adults' rMRE under valid cues (14.0%) was significantly greater than under invalid cues (11.2%), $t(26) = 2.19$, $p = 0.038$, $d = 0.42$, 95% CI = [0.16, 5.32].

Finally, independent-samples t-tests were conducted on rMRE values for each participant type under valid and invalid cue conditions. As shown in Figure 2(c), under valid cue conditions, younger adults' rMRE (14.0%) was significantly greater than older adults' rMRE (7.9%), $t(53) = 4.46$, $p < 0.001$, $d = 1.20$, 95% CI = [3.33, 8.79]. Under invalid cue conditions, younger adults' rMRE (11.2%) was also significantly greater than older adults' rMRE (5.2%), $t(53) = 3.50$, $p < 0.001$, $d = 0.94$, 95% CI = [2.59, 9.51].

4.2.3 Race Model Analysis First, cumulative probability values were calculated at 10 ms intervals from 100–1200 ms for auditory $P(RT_A < t)$, audiovisual $P(RT_{AV} < t)$, and visual $P(RT_V < t)$ responses for both older and younger adults under each cue type condition. The cumulative probability difference between the race model CDF $P(RT_{\text{Race model}} < t)$ and the audiovisual CDF $P(RT_{AV} < t)$ was then computed, with one-tailed one-sample t-tests conducted at each 10 ms interval following Nardini et al. (2016).

Results for older adults are shown in Figure 5 Figure 5: see original paper and (b): Under valid cue conditions, the significant race model violation window was 90 ms (160–250 ms), $ts(27) > 1.88$, $ps < 0.05$, $ds > 0.36$, with a peak at 210 ms of 2.07%. Under invalid cue conditions, no significant race model violation window emerged, indicating that older adults showed stronger audiovisual integration effects under valid versus invalid cue conditions.

Results for younger adults are shown in Figure 5(c) and (d): Under valid cue conditions, the significant race model violation window was 150 ms (120–270 ms), $ts(26) > 1.96$, $ps < 0.05$, $ds > 0.38$, with a peak at 190 ms of 7.14%. Under invalid cue conditions, the violation window was 130 ms (160–180 ms; 190–300 ms), $ts(26) > 2.06$, $ps < 0.05$, $ds > 0.40$, with a peak at 270 ms of 4.87%. A paired-samples t-test comparing peaks showed no difference, $t(26) = 1.38$, $p = 0.089$. Thus, although younger adults showed earlier onset and longer violation windows under valid versus invalid cue conditions, the absence of peak differences indicates comparable audiovisual integration magnitude across cue conditions.

General Discussion

This study used an endogenous spatial cue-target paradigm across three experiments to examine how endogenous spatial attention affects audiovisual integration in older and younger adults under varying cue validity conditions. The results revealed that younger adults' audiovisual integration effects were stronger than older adults' across all valid cue conditions (Figure 2). Furthermore, the influence of endogenous spatial attention on audiovisual integration differed between older and younger adults depending on cue validity. Older adults' rMRE and race model results indicated that endogenous spatial attention did not facilitate audiovisual integration at 50% and 70% cue validity, but did promote integration at 90% cue validity. Younger adults' rMRE and race model results showed that endogenous spatial attention did not facilitate audiovisual integration at 50% cue validity, but significantly promoted integration at 70% and 90% cue validity.

Across all cue validity conditions, younger adults exhibited stronger audiovisual integration effects than older adults under valid cue conditions (Figure 2). Previous research on audiovisual integration in aging has yielded two competing perspectives. The first suggests that older adults show stronger audiovisual integration than younger adults, proposing that this reflects compensation for age-related declines in unimodal sensory function (Laurienti et al., 2006). The second perspective holds that audiovisual integration is weaker in older adults due to factors such as stimulus location (Wu et al., 2012). Our findings support the second view. In the present study, target stimuli always appeared in peripheral locations (left/right at 11° eccentricity), and older adults showed slower response times than younger adults across all stimulus types (Tables 2, 3, and 4), indicating reduced processing capacity in older adults. According to previous research, diminished processing capacity for peripheral stimuli leads to reduced audiovisual integration in older adults (Wu et al., 2012; Yang et al., 2021). Therefore, peripheral stimulus presentation may partially explain why older adults showed weaker audiovisual integration effects in this study. Additionally, while Wu et al. (2012) used random peripheral stimulus locations to examine exogenous spatial attention, the current study employed endogenous spatial attention, requiring participants to voluntarily orient attention based on task demands. Previous research has shown that older adults exhibit lower endogenous attentional orienting benefits than younger adults in endogenous cue-target tasks (Erel & Levy, 2016; Slessor et al., 2016; Zivony et al., 2019).

Consequently, older adults in this study may have required more attentional resources for spatial orienting, leaving fewer resources available for audiovisual stimulus processing and resulting in reduced integration effects compared to younger adults.

Our rMRE and race model analyses revealed that at 50% cue validity, endogenous spatial attention did not facilitate audiovisual integration in either older or younger adults. At 70% cue validity, endogenous spatial attention significantly promoted audiovisual integration in younger adults but not in older adults. At 90% cue validity, endogenous spatial attention significantly facilitated audiovisual integration in both age groups. According to the spatial uncertainty hypothesis, because valid cues and target stimuli provide redundant spatial orienting information, lower cue validity increases uncertainty about target location, causing participants to rely more heavily on cue information for spatial orienting. This reduces the importance of audiovisual target stimuli (van der Stoep et al., 2015) and decreases the attentional resources they receive (唐晓雨 et al., 2020). This may explain why endogenous spatial attention failed to promote audiovisual integration at 50% cue validity. Previous research has shown that as cue validity increases, certainty about target location also increases, reducing the need for spatial orienting and allowing more attentional resources to be allocated to audiovisual stimuli under valid cue conditions, thereby promoting integration (van der Stoep et al., 2015; 彭姓 et al., 2019; 唐晓雨 et al., 2020). This accounts for the significant facilitation observed at 70% cue validity in younger adults. Notably, the absence of facilitation in older adults at 70% cue validity may reflect their inability to allocate additional attentional resources to audiovisual stimuli under valid cue conditions. Zivony et al. (2019) demonstrated that older adults show lower endogenous attentional orienting benefits than younger adults at 75% cue validity, resulting in greater uncertainty about target location. In the present study, at 70% cue validity, older adults likely experienced higher spatial uncertainty than younger adults, leading to fewer attentional resources allocated to audiovisual stimuli under valid cue conditions and consequently no integration facilitation. However, as cue validity increased to 90%, endogenous spatial attention facilitated audiovisual integration in both age groups. Research has shown that at high cue validity levels, older adults' endogenous attentional orienting benefits are comparable to those of younger adults (Folk & Hoyer, 1992). Thus, at 90% cue validity, both older and younger adults could effectively use endogenous cues for spatial orienting, allocating more attentional resources to audiovisual stimuli under valid cue conditions and promoting integration.

In conclusion, under endogenous spatial attention conditions: (1) older adults showed weaker audiovisual integration than younger adults regardless of cue validity level; and (2) the modulatory effects of endogenous spatial attention on audiovisual integration differed between age groups depending on cue validity, with facilitation of older adults' audiovisual integration occurring only under high cue validity conditions.

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