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Age-Related Effects on Cross-Modal Duration Perception

Alexandra N. Scurry[1,*], **Dustin Dutcher**[1], **John S. Werner**[2], **Fang Jiang**[1]

[1]Department of Psychology, University of Nevada, Reno, NV 89557, USA

[2]Department of Ophthalmology and Vision Science, University of California, Davis Medical Center, Sacramento, CA 95817, USA

Abstract

Reliable duration perception of external events is necessary to coordinate perception with action, precisely discriminate speech, and for other daily functions. Visual duration perception can be heavily influenced by concurrent auditory signals; however, age-related effects on this process have received minimal attention. In the present study, we examined the effect of aging on duration perception by quantifying (1) duration discrimination thresholds, (2) auditory temporal dominance, and (3) visual duration expansion/compression percepts induced by an accompanying auditory stimulus of longer/shorter duration. Duration discrimination thresholds were significantly greater for visual than auditory tasks in both age groups, however there was no effect of age. While the auditory modality retained dominance in duration perception with age, older adults still performed worse than young adults when comparing durations of two target stimuli (e.g., visual) in the presence of distractors from the other modality (e.g., auditory). Finally, both age groups perceived similar visual duration compression, whereas older adults exhibited visual duration expansion over a wider range of auditory durations compared to their younger counterparts. Results are discussed in terms of multisensory integration and possible decision strategies that change with age

Keywords

Cross-modal duration perception; aging; multisensory integration

1. Introduction

Enhanced resolution of a sensory system in a particular domain often influences how sensory signals from other modalities are perceived. For instance, the visual system has enhanced spatial perception (for review see Witten and Knudsen, 2005) and can influence the localization of a sound when the spatial locations of auditory and visual signals are incongruent, an effect termed spatial ventriloquism (Alais and Burr, 2004; Mateeff *et al.*, 1985). Audition is fine-tuned for temporal discrimination (Walker and Scott, 1981; Welch *et al.*, 1986), therefore the temporal attributes of a sound can influence the temporal perception

*To whom correspondence should be addressed. ascurry@unr.edu.

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of a co-occurring visual signal. For instance, the onset of a visual flash is perceived closer in time to the physical onset of a subsequent or preceding sound (Fendrich and Corballis, 1999, 2001) and the perceived flicker rate of a visual stimulus can be distorted by the flutter rate of an auditory click (Shipley, 1964). Auditory influence over visual perception is highly dependent on the temporal proximity between the two signals. This is demonstrated in the sound-induced flash illusion (SIFI), where sequential auditory beeps that are close together in time and accompany visual flashes can perceptually modify visual temporal characteristics and influence the number of perceived flashes (Shams *et al.*, 2000, 2002). Auditory dominance has been particularly evident in multisensory duration perception where auditory signals influence the perceived length of a visual signal (Burr *et al.*, 2009; Chen and Yeh, 2009; Klink *et al.*, 2011; Ortega *et al.*, 2014; Romei *et al.*, 2011). Walker and Scott (1981) initially reported that the perceived duration of an audiovisual stimulus was closer to the perceived duration of the auditory stimulus rather than the visual stimulus. Even when an auditory signal has a lower perceived salience than a visual signal or when the visual system is selectively attended to, auditory cues still dominate visual duration perception (Ortega *et al.*, 2014), often to a greater extent than predicted by auditory duration discrimination thresholds (Burr *et al.*, 2009). Despite the extensive literature investigating the principles underlying cross-modal duration perception, little attention has been given to the effect of aging on these cross-modal duration percepts.

As precise and reliable time perception is central to virtually all psychological phenomena and daily experiences, it is critical to understand how duration perception can be impacted by age. Indeed, duration perception is highly flexible (Johnston *et al.*, 2006; Walker and Scott, 1981) and can have a major influence on an individual's subjective experience (Pöppel, 1997). Precise duration judgments are integral for accurate speech perception (Fogerty, 2013; Gordon-Salant *et al.*, 2006), motor coordination (Mauk and Buonomano, 2004; Rao *et al.*, 1997), and estimating time to cross a road with busy traffic (Naveteur *et al.*, 2013). Further, when auditory and visual stimuli of unequal duration are paired together, the perceived synchrony of the two signals is modulated (Kuling *et al.*, 2012). A longer auditory stimulus must be presented earlier than the visual in order to preserve synchrony perception, suggesting an influence of cross-modal duration perception on perceived stimulus onset (Kuling *et al.*, 2012). Changes to this perceptual process could have significant implications for older adults' daily experience, motor actions, and judgment of presumed synchronous events (e.g., speech) in which the length of the individual sensory signals making up the multisensory event are unequal.

While there is evidence for age-related impairments for unisensory duration discrimination in both visual (Lustig and Meck, 2011) and auditory tasks (Fitzgibbons and Gordon-Salant, 1994, 1995; Kumar and Sangamanatha, 2011), age-related effects on multisensory duration perception remain unknown. However, as age-related deficits are found in other multisensory temporal processes, it is likely that cross-modal duration perception is also affected by aging. These age-related multisensory temporal processing impairments depend on both task and stimulus (for review see Brooks *et al.*, 2018). For instance, older adults show greater susceptibility to the fission, not fusion, version of the SIFI (McGovern *et al.*, 2014) and reduced sensitivity to temporal delays between auditory and visual signals during a temporal order judgement task, but not a simultaneity judgment task (Bedard and Barnett-

Cowan, 2016). In addition, older adults show reduced sensitivity at detecting auditory rate modulation but retain precise weighting of visual and auditory information for coherent integrated percepts (Brooks *et al.*, 2015).

Multiple studies reveal less precise multisensory integration in older adults, evidenced by a higher propensity to perceptually bind stimuli over longer temporal delays in older individuals (Baum and Stevenson, 2017; Bedard and Barnett-Cowan, 2016; Chan *et al.*, 2014; Setti *et al.*, 2011). These findings predict age-related changes in cross-modal duration perception, as multisensory integration is a potential main driver of cross-modal duration perception. When auditory and visual cues of unequal durations were presented with synchronous onsets, visual duration discrimination was impaired (Romei *et al.*, 2011). These observations were explained by proposing that the auditory stimulus shifts the perceived on- and/or offset of the visual stimulus toward the sound via multisensory integration. This hypothesis was further supported by the finding that, when the duration of the auditory stimulus was tripled in length such that the offsets of the two cues were far apart in time, the impairment in visual duration discrimination was attenuated (Romei *et al.*, 2011), as multisensory integration is known to depend on the temporal coincidence of the signals. Even when the auditory signal lacked any duration information (e.g., a brief auditory pulse), auditory signals presented at ±50 ms to the onset/offset of a full visual signal still shifted visual duration judgements of young adults, likely through audiovisual binding of stimulus on- or offsets (Bausenhart *et al.*, 2014). In contrast, manipulations used to prevent audiovisual binding in young adults, such as using large asynchronous onsets of the two cues (e.g., 500 ms), attenuated the influence of audition on visual duration perception (Romei *et al.*, 2011).

The temporal limits on cross-modal duration perception in young adults were explored by Klink *et al.* (2011). When an audiovisual pair was presented and the auditory tone was physically longer (or shorter) than the visual stimulus, that visual signal was perceived as being longer (or shorter) than its veridical duration due to perceptual duration expansion (or compression) (Bausenhart *et al.*, 2014; Burr *et al.*, 2009; Klink *et al.*, 2011). Duration expansion and compression of visual cues in young adults was induced by pairing auditory stimuli of durations between 150 and 850 ms with a 500 ms standard visual stimulus (Klink *et al.*, 2011). However, the degree of the visual expansion and compression percept diminished when the sound was 200 ms longer and 350 ms shorter than the visual, respectively (Klink *et al.*, 2011). As older adults are more likely to combine auditory and visual information despite large temporal separation (Baum and Stevenson, 2017; Bedard and Barnett-Cowan, 2016; Setti *et al.*, 2011), we hypothesized that older individuals would exhibit visual duration expansion and compression over a wider range of audiovisual duration differences than young adults. Using a similar procedure to that of Klink *et al.* (2011), we measured the temporal constraints of auditory dominance over vision in duration perception.

As this experimental design assumes asymmetric cross-modal influence on duration perception, we also investigated the extent of this asymmetry in natural aging. Participants discriminated the longer of two target stimuli in the presence of non-target stimuli. The durations of the target signals were based on participant’s unisensory discrimination thresholds. If no cross-modal influence occurred, we expected to see performance similar to the criteria used for estimating thresholds. When non-target stimuli did exert influence on duration perception of the target, we expected a decrease in performance. Under this scenario when the non-target stimuli are equal in duration, discrimination should be extremely difficult and performance should drop to chance. When the non-target stimuli are unequal (one longer and one shorter), we expect to induce expansion and compression percepts, respectively, and find below chance performance. As our experimental design was developed from Klink *et al.* (2011), we expected a similar unidirectional influence, from audition to vision, for both age groups. Without evidence that one modality deteriorates to a greater extent than the other in healthy aging, we hypothesized that audition would retain dominance over vision in the temporal domain. Further, we expected worse overall performance by older adults regardless of target modality because susceptibility to distracting information increases with age during heightened attentional and task demands (Alain and Woods, 1999; Andrés *et al.*, 2006; Harris *et al.*, 2011).

2. Material and Methods

2.1. Participants

In Experiment 1, twenty-two older adults (65–73 years; $M = 68.6 \pm 2.2$ years; 15 females) and twenty-five young adults (18–28 years;=$M = 21.9 \pm 2.8$ years; 19 females) participated. In Experiment 2, twenty older adults (65–74 years; $M = 69 \pm 2.3$ years; 14 females) and twenty younger adults (19–28 years; $M = 22.6 \pm 2.9$ years; 15 females) participated (twenty of the older and nineteen of the younger adults were from Experiment 1). Sample sizes were chosen based on main effects from prior studies (Bausenhart *et al.*, 2014; Klink *et al.*, 2011) and a power analysis using a minimal partial effect size ($\eta^2 = 0.06$) for the main interactions of interest (Threshold: Age × Modality; Exp. 1: Age × Target Modality; Exp. 2: Age × Auditory Test Duration) with 90% power. Subjects were recruited from the University of Nevada, Reno and the surrounding community. All subjects reported normal or corrected to normal vision. Participants were verbally screened for any history of neurological or psychiatric disorders, history of brain injury, antipsychotic medications and cognitive decline. Older adults were additionally screened using AudioScope 3, a screening audiometer (Welch Allyn, Skaneateles Falls, NY, USA) and were required to have a pure tone threshold lower than 40 dB for 1 and 2 kHz following the criteria of Ventry and Weinstein (1983). Participants provided signed informed consent before any experimentation and were financially compensated for their time. Protocols were reviewed and approved by the Institutional Review Board at the University of Nevada, Reno.

2.2. Stimuli and Experimental Setup

Stimuli were generated using MATLAB (Mathworks, Natick, MA, USA) and Psychtoolbox extensions (Brainard, 1997; Pelli, 1997). The visual stimulus was a stationary white circle with a diameter of 3.5° presented on a grey background in the center of the screen. Auditory stimuli were pure tones of 1000 Hz created in MATLAB and presented binaurally at 75 dB (measured at the auditory source) via Sennheiser HD 280 pro headphones laid flat, directly under the center of the display, with earpieces facing the ceiling to approximate the same spatial location as the visual signal. Visual and auditory stimuli were delivered through a

Display ++ system with a refresh rate of 120 Hz and an AudioFile stimulus processor, respectively (Cambridge Research Systems, Rochester, UK). For all experiments, participants sat in front of the display 60 cm away from the screen.

2.3. Measuring Duration Discrimination Sensitivity

Following Klink *et al.* (2011), unisensory and cross-modal discrimination thresholds were estimated to normalize stimuli for all participants completing Experiment 1. An adaptive staircase procedure using the Quest algorithm was applied to determine duration discrimination thresholds in the visual only (V), auditory only (A), and audio-visual (AV) conditions. In the A and V conditions, the standard and test stimuli were from the same modality. In the AV condition, the standard stimulus was always the visual signal, while the test stimulus was always the auditory signal with varying durations.

At the start of each trial, a standard stimulus of 500 ms was presented followed by a test stimulus separated by a variable inter-stimulus interval (ISI) between 1900 and 2100 ms (Fig. 1, top panel). The duration of the test stimulus was determined in each trial by a QUEST procedure, a Bayesian algorithm that uses prior knowledge of duration discrimination thresholds and the data from previous trials (Watson and Pelli, 1983). Using an average threshold estimate from unisensory visual and auditory duration discrimination tasks, we set the prior to 100 ms with 3 ms SD for all conditions (Klink *et al.*, 2011; Kumar and Sangamanatha, 2011). Possible durations for both the auditory and visual test stimuli were between 50 and 1000 ms in 5 ms intervals. The task was modeled as a 2AFC task with gamma = 0.5 and the IV was the difference in duration of the test stimulus relative to the standard duration (500 ms). Whether the test stimulus was shorter or longer than the standard was pseudo-randomized so that on half of the trials the test stimulus was shorter and on the other half the test stimulus was longer. Participants were asked to verbally respond as to whether the second stimulus (always the test) was shorter or longer than the first stimulus (always the standard). Participants completed three experimental blocks for each condition. In each block, participants performed 40 trials converging on 82% correct, an optimal criterion for a QUEST procedure (Watson and Pelli, 1983). The order of experimental conditions was randomized across participants within each age group.

The average threshold was computed for each condition (V, A, and AV) and reported as the subject's 82% threshold, the point where the subject could reliably differentiate the difference in physical duration of two stimuli on 82% of the trials.

2.4. Experiment 1 — Cross-Modal Influence on Duration Perception

Using each participant's unisensory duration discrimination thresholds, we tested the influence of auditory information on visual perception and vice versa. In the visual target condition, participants were asked to focus on the visual stimuli and ignore the auditory information. In the auditory target condition, participants were asked to attend to the auditory stimuli and ignore the visual stimuli. Participants were presented with a black fixation cross on a computer monitor for 500 ms followed by a blank screen for 1000 ms to signal the start of a trial. On each trial, two AV center-aligned pairs were presented with their center-points separated by a variable ISI between 1450 and 1550 ms. Participants were asked to determine if the second target stimulus was shorter or longer than the first target stimulus via a keyboard press.

As shown in the middle panel of Fig. 1, the target's duration (e.g., visual stimulus length) was based on the participant's unisensory target threshold (e.g., visual duration discrimination threshold) and had two possible durations: (1) 500 ms − threshold/2 (Short) or (2) 500 ms + threshold/2 (Long). The non-target stimulus had three possible durations: 400, 500, or 600 ms. In half of the trials, the non-target stimulus in both AV pairs was equal in duration (NT-same; always 500 ms) (top group of middle panel in Fig. 1). In the other half of trials, the non-target stimulus was shorter in one pair (400 ms) and longer in the other pair (600 ms) (NT-different) (bottom group of middle panel in Fig. 1). In these NT-different trials, the longer non-target stimulus (600 ms) was always paired with the shorter target (500 ms − threshold/2) while the shorter non-target stimulus (400 ms) was always paired with the longer target (500 ms + threshold/2). In half of the NT-same trials, the shorter target was presented first while in the other half of NT-same trials the longer target was presented first (as shown in the middle panel of Fig. 1). In half of the NT-different trials, the shorter target (paired w/longer non-target) was presented first while in the other half the longer target (paired w/shorter non-target) was presented first (as shown in the middle panel of Fig. 1). Each of the four possible combinations was repeated 20 times in a randomized order for a total of 80 trials, separated into two experimental blocks. The percentage of correctly identified longer target stimuli was calculated and compared to the criterion used to define the duration discrimination threshold (e.g., 82%) and to chance level (e.g., 50%).

2.5. Experiment 2 — Compression and Expansion Effects of Visual Duration Perception

In this experiment, participants were instructed to attend to the visual stimuli and ignore the auditory information. Each trial started with a fixation cross for 500 ms followed by a blank screen for 1000 ms. Two AV center-aligned pairs were then presented with their center-points separated by an ISI varying between 1450 and 1550 ms. At the end of each trial, participants were asked to judge whether the visual stimulus in the second AV pair was shorter or longer than the visual stimulus in the first AV pair. As seen in Fig. 1C, one AV pair was the standard and one was the test, unlike the study of Klink *et al.* (2011) that used a visual-only standard. In the standard AV pair, both the visual and auditory stimuli were 500 ms. In the test AV pair, a 500 ms visual stimulus was presented with an auditory stimulus varying in duration from 100 to 900 ms, in steps of 50 ms (17 total). Each of the 17 A test durations were presented nine times for the stimulus order 'standard AV pair first' and nine times for the stimulus order 'test AV pair first'. There was a total of 306 trials separated into three blocks (102 trials each). Similarly to Exp. 1, participants were asked to respond via a keyboard press if they thought the second visual stimulus was on the screen for a shorter or longer duration than the first visual stimulus. The percentage of visual stimuli in the test AV pairs judged longer than the visual stimuli in the standard AV pairs was calculated and plotted as a function of A test duration.

2.6. Analysis

Mixed ANOVAs and *t*-tests with multiple comparison correction were used to compare differences between age groups and conditions of each experiment. To control for the potential effect of gender, we conducted mixed ANOVAs and found that gender was not a significant factor in predicting discrimination thresholds [$F(1,43) = 2.08$, $p = 0.16$], in Experiment 1 [$F(1,43) = 0.61$, $p = 0.44$], or in Experiment 2 [$F(1,36) = 0.12$, $p = 0.73$]. Thus, gender was not included as a factor in subsequent mixed ANOVAs. Statistical analysis was performed in R version 1.1.463 using the lme4 package (Bates *et al.*, 2015).

3. Results

3.1. Duration Discrimination Thresholds

The duration discrimination thresholds in the auditory (A), visual (V), and audiovisual (AV) conditions were determined prior to Experiments 1 and 2 using an adaptive staircase procedure. Figure 2 shows the group average from all three conditions for young (A: 58.7 ± 3.7 ms; V: 112.6 ± 8.1 ms; AV:95.6 ± 11.3 ms) and older (A: 59.3 ± 5.8 ms; V: 109.0 ± 11.8 ms; AV: 91.7 ± 8.8 ms) adults. Results from a two-way, mixed 3 (modality: A, V, AV) × 2 (age: old vs. young) ANOVA did not reveal a significant main effect of age [$F(1,45) = 0.08$, $p = 0.78$, partial $\eta^2 = 0.001$] or any significant interaction between age and modality [$F(2,90) = 0.06$, $p = 0.94$, partial $\eta^2 = 0.001$]. However, there was a main effect of modality [$F(2,90) = 25.67$, $p <= 0.001$, partial $\eta^2 = 0.22$]. Post-hoc pairwise comparisons with Bonferroni correction revealed that A thresholds were significantly lower than both V ($p < 0.001$) and AV ($p < 0.001$) while there was no difference between AV and V thresholds ($p = 0.15$).

3.2. Experiment 1: Cross-Modal Influence

Next, we investigated if aging impacted auditory or visual dominance in cross-modal duration perception (Experiment 1). Figure 3 shows average accuracy in determining the longer target stimulus. The left panel plots the A target condition paired with a V non-target stimulus of the same (Older adults: 67.9 ± 2.4%; Young adults: 78.5 ± 1.8%) and of different duration (Older adults: 68.7 ± 3.0%; Young adults: 74.4 ± 2.1%). The right panel shows the V target condition paired with an A non-target stimulus of the same (Older adults: 53.6 ± 2.3%; Young adults: 58.6 ± 2.1%) and of different duration (Older adults: 11.6 ± 3.1%; Young adults: 16.3 ± 2.6%).

Initially, a three-way mixed ANOVA was performed with target modality (A, V) and non-target stimulus duration (same, different) as within-subject factors and age (young, old) as a between-subjects factor. There was a significant main effect of age [$F(1,45) = 11.75$, $p < 0.01$, partial $\eta^2 = 0.073$], but no significant interaction between age and target modality [$F = (1,45) = 0.60$, $p = 0.44$, partial $\eta^2 = 0.005$], between age and non-target stimulus duration [$F(1,45) = 0.78$, $p = 0.38$, partial $\eta^2 = 0.003$], or between age, non-target stimulus duration and target modality [$F = (1,45) = 0.78$, $p = 0.39$], indicating that overall older adults performed less accurately than young adults across conditions. While there was a significant main effect of target modality [$F(1,45) = 309.49$, $p < 0.001$, partial $\eta^2 = 0.723$], and a significant main effect of non-target stimulus duration [$F(1,45) = 229.43$, $p < 0.001$, partial $\eta^2 = 0.473$], these were qualified by a significant interaction [$F(1,45) = 238.37$, $p < 0.001$, partial $\eta^2 = 0.430$]. Two separate one-way ANOVAs, using a corrected alpha level of 0.025, revealed an effect of the non-target duration in the V target condition [$F(1,46) = 400.1$, $p <$

0.001, partial $\eta^2 = 0.075$], but not the A target condition [$F(1,46) = 1.05$, $p = 0.31$, partial $\eta^2 = 0.007$].

Separate one-sided *t*-tests using Bonferroni-corrected *p* values of 0.003125 (0.05/16) were conducted for each group in both target conditions. In the NT-different condition, performance for young adults was significantly below the 82% criteria for both target modalities [V: $t(24) = 24.93$, $p < 0.001$; A: $t(24) = 3.62$, $p < 0.001$] and significantly below chance level for the V target [($t(24) = 12.78$, $p < 0.001$], but not A target [$t(24) = 11.73$, $p = 1$]. The same pattern was found for older adults at both 82% [V: = $t(21) = 22.67$, $p < 0.001$; A: $t(21) = 4.37$, $p < 0.001$] and at 50% [V: $t(21) = 12.40$, = $p < 0.001$; A: $t(21) = 6.13$, $p = 1$]. Thus, auditory distractor information impacts visual duration perception to a greater extent than visual distractors influence auditory duration perception, regardless of age. In the NT-same condition, young adults still performed significantly worse than 82% in the V target [$t(24) = 11.11$, $p < 0.001$], not A target condition [$t(24) = 1.88$, $p = 0.04$], but not significantly below chance in either target condition [V: $t(24) = 4.08$, $p = 0.99$; A: $t(24) = 15.47$, $p = 1$]. Similarly, the older group performed below the 82% criteria in the V target [$t(21) = 12.51$, $p < 0.001$], not A target condition [$t(21) = 7.37$, $p = 1$], but not different than 50% [V: $t(21) = 1.57$, $p = 0.93$; A: $t(21) = 7.37$, $P = 1$] suggesting that discrimination of target duration differences was not better than chance performance and that decreased accuracy in the NT-same condition was influenced by auditory, not visual distracting information. As seen in Fig. 3, when the visual non-target stimuli had equal durations, older adults performed worse than young adults. Since the purpose of Experiment 1 was to identify age-related changes to cross-modal influence on duration perception, a two-sided independent *t*-test was conducted and revealed that this difference was indeed significant [$t(45) = 3.53$, $p < 0.001$].

3.3. Experiment 2: Visual Perceptual Expansion and Compression

We next examined how unilateral visual expansion and compression was affected by age over a range of A test durations (Experiment 2). In Fig. 4, the percentage of trials when the V stimulus in the test AV pair was perceived as longer than the V stimulus in the standard AV pair is plotted as a function of the A test duration. Note that there was an outlier in the older dataset (see Supplementary Figs S1–S3 for individual data); however, removing this subject did not affect results so he was included for subsequent analyses. We conducted a three-way mixed ANOVA with A duration (100 to 900 ms at 50 ms steps) and order of AV pairs (standard first, test first) as within-subject factors and age (young, old) as a between-subjects factor. The main effects of age [$F(1,38) = 2.71$, $p = 0.11$, partial $\eta^2 = 0.006$] and order [$F(1,38 = 0.68$, $p = 0.41$, partial $\eta^2 = 0.003$] were significant not while the main effect of A test duration was [$F(16, 608) = 215.06$, $p < 0.001$, partial $\eta^2 = 0.728$]. There was also a significant three-way interaction between age, order, and A test duration [$F(16,608) = 2.09$, $p < 0.01$, partial $\eta^2 = 0.014$].

To examine this three-way interaction, we held the presentation order constant and performed two-way mixed ANOVAs (within-subject factor: A duration; between-subjects factor: age). When the test AV pair was presented first (Fig. 4, middle panel) there was no significant effect of age [$F(1,38) = 0.073$, $p = 0.79$], but there was a significant effect of A test duration [$F(16,608) = 148.01$, $p < 0.001$], and a significant interaction between age and A test duration [$F(16,608) = 1.75$, $p = 0.034$]. Post-hoc analysis revealed that age was not a factor at any A test duration after correcting for multiple comparisons [ts(38) < 2.35, all ps ⩾ 0.02]. The analysis on the standard-first subset (Fig. 4, right panel) also revealed a significant interaction between age and A duration [$F(16, 608) = 3.59$, $p < 0.001$)]. Post-hoc tests showed that the age effect on duration expansion remained significant when the auditory test duration was 850 and 900 ms [ts(38) > 2.75, ps < 0.009].

To evaluate compression and expansion effects at each A test duration for both groups, separate t-tests with Bonferroni correction were performed on the data collapsed over stimulus order. If participants experienced a significant expansion (or compression) effect, their response of 'Longer test visual stimulus' should be significantly greater than (less than) chance. Young adults experienced significant visual compression with A test stimuli between 100 and 450 ms [ts(19) between −3.89 and 35.99, all ps < 0.001] and a significant expansion effect for A test durations between 550 and 850 ms [ts(19) between 3.45 and 8.06, all ps < 0.0027]. This effect did not survive multiple comparison correction at the maximum A test duration of 900 ms [$t(19) = 1.73$, $p = 0.1$]. Young adults did not reveal any effect when the A and V stimuli in the test AV pair were the same 500 ms duration [$t(19) = 0.39$, $p = 0.7$].Results for older adults also revealed duration compression across all A test durations shorter than 500 ms [ts(19) between −7.54 and 26.87, all ps < 0.0001]. Similarly, older adults had significant expansion percepts for all A test durations greater than 500 ms [ts(19) between 3.78 and 11.36, all ps < 0.0013]. When the A duration was 500 ms, response accuracy of older adults was not significantly different from chance [$t(19) = 0.64$, $p = 0.53$].

4. Discussion

We sought to characterize how aging impacts auditory and visual duration discrimination and cross-modal duration perception. While there was no effect of age on duration discrimination thresholds or on auditory dominance over visual duration perception, older adults did perform less accurately when judging durations of target stimuli in the presence of non-target stimuli. In addition, both young and older adults perceived duration compression of the visual stimulus when its paired auditory signal was shorter than the standard 500 ms. For sounds longer than the standard, older adults maintained visual duration expansion across A test durations longer than the standard while young adults perceived visual duration expansion at all A test durations longer than the standard except for the maximum, 900 ms. However, stimulus order did influence the expansion effect in young adults, not older adults, with more robust expansion at longer auditory test durations for trials where the test pair was presented first.

4.1. No Effect of Age on Duration Discrimination Thresholds

When assessing duration discrimination sensitivity, a similar pattern was observed for both age groups. Auditory thresholds were significantly lower than visual and audiovisual thresholds supporting the notion of enhanced temporal resolution in the auditory domain (Walker and Scott, 1981; Welch *et al*., 1986). As older adults show declines in unisensory processing (Andersen, 2012; Howarth and Shone, 2006; Owsley, 2011; Werner *et al*., 2010) and reduced temporal acuity within the auditory and visual system (Brooks *et al.*, 2018; Fitzgibbons and Gordon-Salant, 1994, 1995; Kumar and Sangamanatha, 2011; Pütz *et al.*, 2012; Ulbrich *et al.*, 2009), we expected impaired duration discrimination in the older group. Absence of an age effect may be due to the simplicity of the stimuli used. Studies also reporting no effect of age on discrimination sensitivity used simple auditory pure tones (Rammsayer *et al.*, 1993) or static visual stimuli (Lustig and Meck, 2011). Conversely, age-related deficits on duration perception were found with complex stimuli, such as dynamic speech (Lister and Tarver, 2004) or white noise (Kumar and Sangamanatha, 2011), and with a complex task where the target tone was embedded in a random location within a sequence of tones (Fitzgibbons and Gordon-Salant, 1995). While the results reported here show intact processes in older adults, future studies that explicitly address the ecological validity of stimuli in cross-modal duration perception are needed.

4.2. Uni-Directional Cross-Modal Influence on Duration Perception Is Retained in Older Adults

While the non-target stimulus only showed a significant main effect when the target signal was visual, both groups showed performance below 82% when the non-target stimulus had different durations, regardless of the target modality. Other studies also show cross-modal influence in the visual to auditory direction, when reducing and heightening the perceptual saliencies of the sound and visual signal, respectively (Walker and Scott, 1981), or when using empty intervals and a smaller range and step sizes of auditory test durations (367–634 ms at ~30 ms steps) (Bausenhart *et al.*, 2014). Similar to these studies, the present bidirectional cross-modal influence is clearly asymmetric. A robust effect for auditory influence over visual duration discrimination was especially apparent when examining the NT-different conditions. The greater influence of audition over vision is presumably due to the heightened resolution of the auditory system in temporal perception (Walker and Scott, 1981; Welch *et al.*, 1986), similar to spatial ventriloquism in localization tasks where more reliable visual spatial cues capture auditory information (Alais and Burr, 2004; Mateeff *et al.*, 1985). Such asymmetric findings are in line with an optimal integration model for duration perception whereby reliability of unisensory duration estimates affects the weighting of each modality when estimating multisensory duration (Hartcher-O'Brien *et al.*, 2014).

The lack of aging effects on auditory dominance is not surprising since both sensory systems decline with age (Howarth and Shone, 2006; Werner *et al.*, 2010). Although older adults also exhibited a similar asymmetric cross-modal influence, this group still performed significantly worse overall when discriminating durations of target stimuli in the presence of non-target stimuli. This finding was most evident when the auditory targets were paired with visual non-target stimuli that were the same duration. Older adults perform significantly worse than young adults despite the absence of a significant cross-modal influence in the visual to auditory direction. Reduced attentional resources (Glisky, 2007) and increased susceptibility to distractors due to deficits in top-down attentional control (Alain and Woods, 1999; Andrés *et al.*, 2006), characteristic of older adults, may account for this effect. Indeed, older observers underestimate visual duration in the presence of auditory distractors, presumably due to an inability to focus on target information and ignore irrelevant information (Lustig, 2003). The inability of older adults to maintain sustained focus when faced with conflicting multisensory signals may lead to biased perceptions or responses toward the most reliable modality.

4.3. Expansion and Compression Effects on Visual Duration Perception Occur Over a Wider Range of Auditory Durations for Older Adults

The second experiment examined the extent of perceptual compression and expansion on visual duration when the V test stimulus of 500 ms was paired with an A stimulus of variable duration. In line with prior findings from young adults (Klink *et al.*, 2011), both age groups showed significant compression percepts along all A test durations shorter than the visual. In contrast, young adults had a slightly limited range over which perceptual expansion occurred, whereas older adults experienced expansion along all A test durations longer than the standard.

These age-related differences may be due to an underlying integrative mechanism. Following temporal ventriloquism, the on/offsets of the visual and auditory stimuli become perceptually bound and shift the perceived duration of the visual signal toward the physical duration of the sound (Bausenhart *et al.*, 2014; Burr *et al.*, 2009; de Haas *et al.*, 2013; Klink *et al.*, 2011). Young adults have enhanced sensitivity to detect temporal discrepancies between signals (Murray *et al.*, 2016; Stevenson *et al.*, 2018) leading to precise integration of cues close together in time and segregation of those with large temporal delays. Therefore, reduced perceptual expansion in this group may be due to detection of the large on/offset difference and subsequent segregation of the A and V signals. Conversely, older individuals are less sensitive to large temporal differences between multisensory signals and are more likely to bind stimuli regardless of their temporal disparity (Baum and Stevenson, 2017; Bedard and Barnett-Cowan, 2016; Brooks *et al.*, 2018; Setti *et al.*, 2011). These participants were likely insensitive to extreme AV duration differences and continued to experience perceptual expansion. The current design found no group differences in the duration discrimination thresholds estimated when comparing a variable auditory test stimulus to a standard visual stimulus, suggesting that unisensory duration discrimination does not predict cross-modal duration perception. Future experiments that estimate multisensory discrimination thresholds (e.g., comparing a standard bimodal stimulus to bimodal test stimuli) may reveal age effects that affect this multisensory rather than unisensory process.

An alternative explanation for the group differences in perceptual expansion may be attentional and decisional bias toward the auditory stimulus as the visual signals (500 ms in both standard and test AV pairs) never provided any reliable temporal information to construct an accurate response. Young adults, who demonstrate flexibility in their response criterion (Brown and Steyvers, 2005; Solomon *et al.*, 2012), could have switched between a ‘respond to auditory’ and a ‘respond to visual’ strategy dependent on the magnitude of the AV duration difference. For instance, when the AV duration difference was small and difficult to discern (e.g., 100 ms), young adults could have used the auditory information to guide their decision. When the AV duration difference was large and more evident (e.g., 400 ms), young adults could have switched decision strategies and attempted to judge the visual stimuli. Conversely, older adults may be less flexible in adjusting decision criteria and always used a 'respond to auditory' strategy. However, studies reporting age-related differences on temporal multisensory tasks (McGovern *et al.*, 2014; Setti *et al.*, 2013) and item-recognition tasks (North *et al.*, 2018) reveal similar response criteria but different perceptual sensitivities between young and old adults. While it is likely that reduced precision in detecting asynchronies is a strong driver of the current results, flexibility in updating response criterion could be task-dependent and a contributing factor.

Age-related differences in multisensory integration and/or response criteria flexibility could also explain why stimulus order only affected young adults. In *standard-first* trials, older adults experienced consistent perceptual expansion while the percept diminished in young adults at maximal A test durations (850 and 900 ms). A 'standard position effect', presumably driven by greater perceptual weight on the second stimulus (Dyjas *et al.*, 2014; Hellström and Rammsayer, 2004, 2015), has been used to describe enhanced unisensory duration discrimination when the standard precedes the test (Bausenhart *et al.*, 2015; Dyjas *et al.*, 2012, 2014; Grondin and McAuley, 2009; Hellström and Rammsayer, 2004, 2015; Lapid *et al.*, 2008; Ulrich, 2010). A special case of this, defined by the Internal Reference Model, describes a more reliable updating of an internal reference on a trial-by-trial basis when the standard (a stable duration) is presented first compared to the test (a variable duration), leading to heightened discrimination sensitivity on standard-first trials (Dyjas et al., 2012). Enhanced sensitivity in standard-first trials could improve detection of the AV temporal disparity and consequently attenuate expansion percepts, as seen in young adults. However, expansion would be retained if duration differences were still beyond detection range, as found in the older group. Alternatively, young adults may shift their decision criterion at large A test durations during standard-first trials, whereas older adults may be less flexible at updating their internal reference, leading to extended visual expansion. Future studies are needed to elucidate decision strategies of older adults when faced with incoherent multisensory duration information.

Interestingly, both groups show perceptual compression across all shorter auditory test durations. This is slightly contrary to the results reported by Klink *et al.* (2011) where the extent of compression begins to attenuate at the shortest auditory test used (150 ms). The current design differed from that in Klink *et al.* (2011) by using an audiovisual standard rather than a visual-only standard. When auditory and visual stimuli of equal durations are presented simultaneously, the duration of the auditory stimulus is perceived as longer than it is physically (Penney *et al.*, 2000; Walker and Scott, 1981; Wearden *et al.*, 1998). Therefore, the duration of the visual stimulus may perceptually expand to match the perceived duration of the auditory stimulus and thus, comparison visual signals would be more likely to be judged as shorter. Such an explanation also accounts for the chance performance by both groups when the auditory test stimulus was equal to the standard duration, as opposed to results of Klink *et al.* (2011) reporting perceptual expansion when the test sound was equal in length to the visual stimulus.

The current findings contribute to our understanding of the age-related impact on one's perception in the context of conflicting multisensory information. However, some limitations including unequal *n*s in Experiment 1 (Exp.1 $n = 22$ for old, $n = 25$ for young), unbalanced samples in gender, and the narrow age range of older adults (65–74 years) might impact the generalizability of these results. A standard cognitive assessment should be used in future screening procedures as individuals with early stages of neurodegeneration are unlikely to self-report any deficits. In addition, visual and auditory acuity measures should also be included in future models. These factors can further parse out aging effects on cross-modal duration perception, as sensory (Andersen, 2012; Howarth and Shone, 2006; Owsley, 2011; Werner *et al.*, 2010) and cognitive decline (Glisky, 2007; Salthouse and Ferrer-Caja, 2003) are common in healthy aging.

5. Conclusions

The present study sought to characterize the impact of aging on duration discrimination sensitivity and cross-modal duration perception. While older adults did not show impaired duration discrimination sensitivity, this group did show greater susceptibility to distracting information from the non-target modality. Further, while perceptual visual expansion in young adults was attenuated as the A test duration increased, particularly in standard-first trials, the percept remained constant for older adults. Reduced attentional capacity, inflexible decision strategies, and increased likelihood of multisensory binding may all contribute to the robust expansion perception in older adults. Additional experiments are needed to parse out the relative contributions of each factor in predicting percepts of older adults when presented with conflicting multisensory information.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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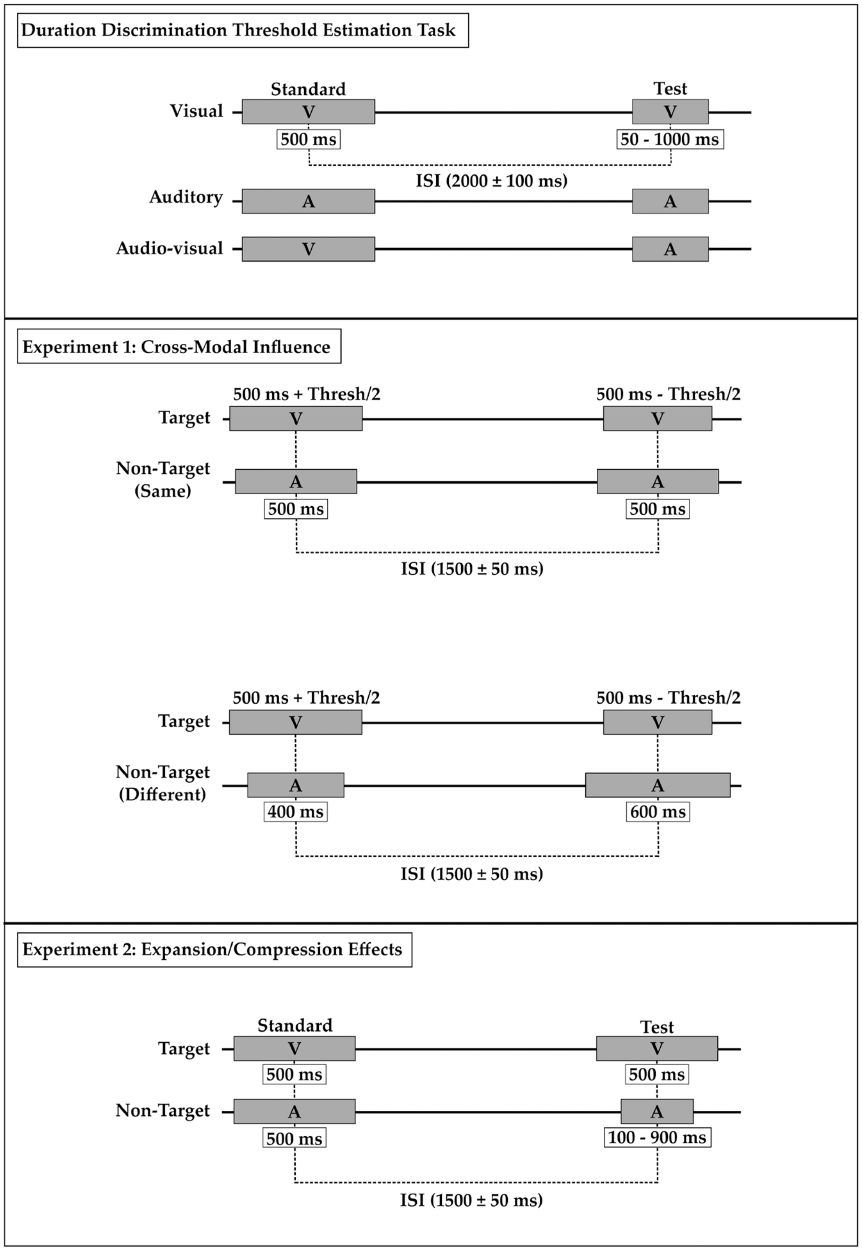

Figure 1.

Experimental designs. Top Panel — Duration discrimination thresholds were measured by presenting a standard stimulus (500 ms) followed by a test stimulus with variable durations (top panel). In the V and A conditions, both the standard and test stimuli were of the same modality while in the AV condition, the standard was always a V stimulus and the test was always an A stimulus. Participants were asked to judge if the second stimulus was shorter or longer than the first. Middle Panel (Exp. 1) — During the NT-same condition (top group), non-target stimuli were 500 ms and target stimuli were 500 ms ± the individual's threshold/2. During the NT-different condition (bottom group), the longer target was always paired with the shorter non-target (400 ms) and the shorter target was always paired with the longer non-target (600 ms). Participants were asked to ignore the non-target signals and judge if the second target stimulus was shorter or longer than the first. This experiment was performed once using V stimuli as the target and A as the non-target (as depicted in the figure) and once using A target stimuli and V non-target stimuli. Bottom Panel (Exp. 2) — The bottom panel depicts the experimental paradigm for Experiment 2. The standard AV pair always consisted of a V and A stimulus that were both 500 ms. The test AV pair always had a V stimulus of 500 ms and an A stimulus of varying durations (depicted as shorter than the visual). Participants were asked to ignore the auditory cues and judge if the second visual stimulus was shorter or longer than the first. For Exp. 1 and 2, the center-points of A and V stimuli were aligned and the ISI was the time between center-points.

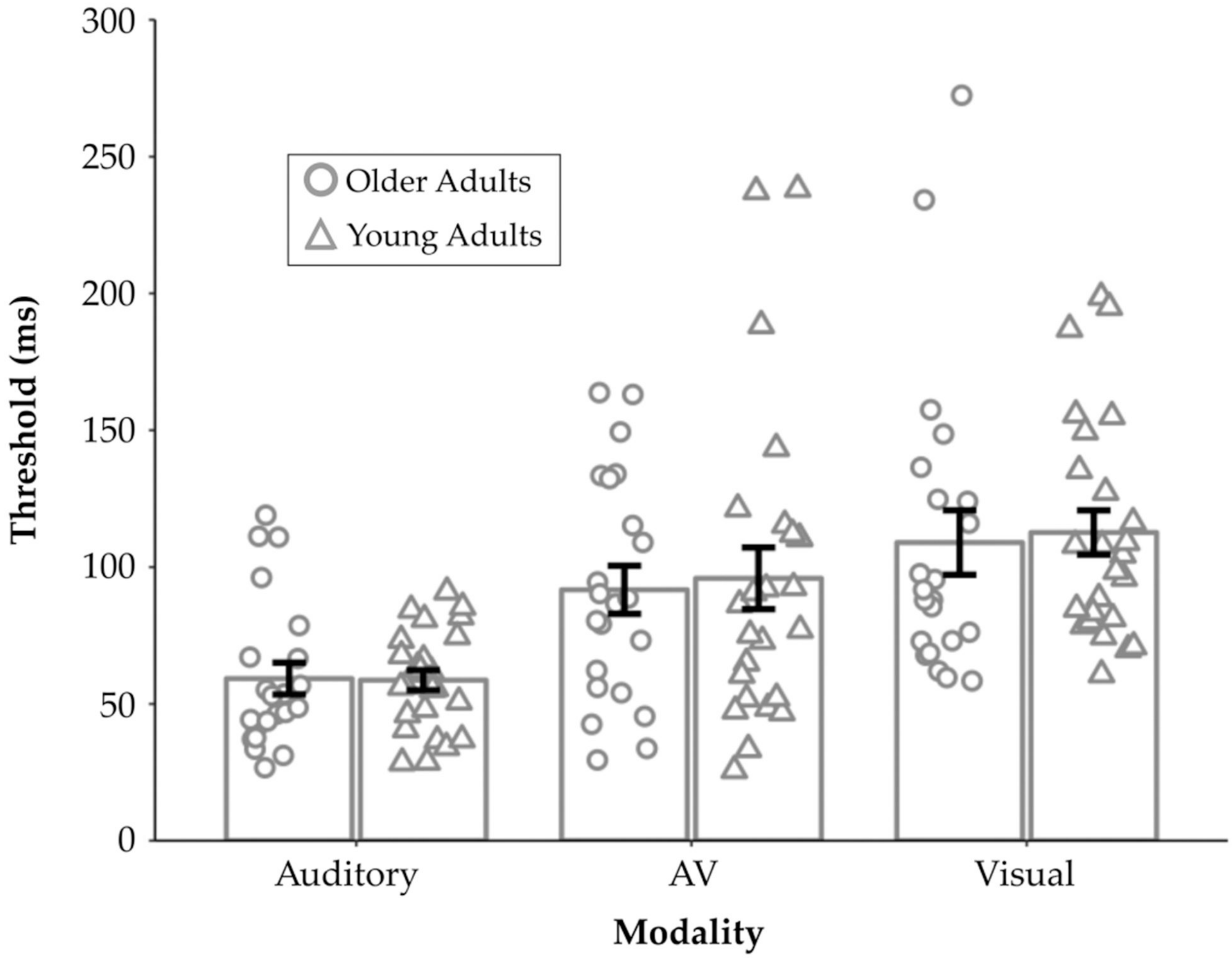

Figure 2.

Duration discrimination thresholds. The average threshold ± SEM along with individual data points are shown for older (circles) and younger (triangles) groups across modalities.There was no effect of age but duration discrimination thresholds were significantly lower for the A modality than for the V or AV.

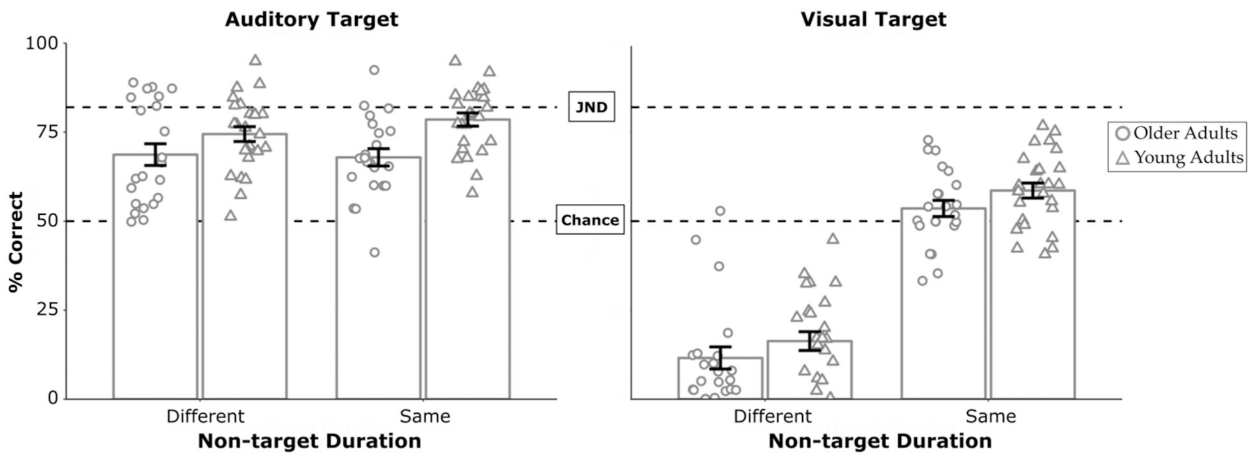

Figure 3.

Auditory dominance over visual duration perception. Individual data points and the average percentage of correct responses for determining the longer target stimulus are shown for older (circles) and young (triangles) adults in the A target condition (left panel) and the V target condition (right panel). Both groups performed significantly below threshold (82%; top dotted line) for the V target condition only. Chance performance (50%) is plotted as the bottom dotted line.

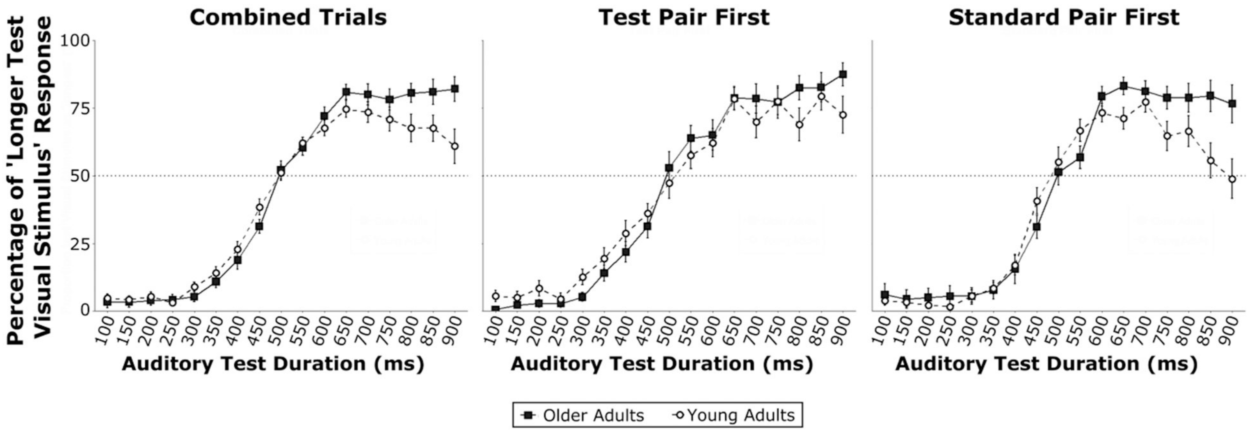

Figure 4.

Expansion and compression effects of visual duration perception. The mean percentage ± SEM of the test V stimulus reported as longer than the standard is plotted as a function of the A test duration for older (black squares and solid line) and young (white circles and dotted line) adults for all trials combined (left panel), test-first trials (middle panel) and standard-first trials (right panel). Chance performance (50%) is plotted as the dotted line.