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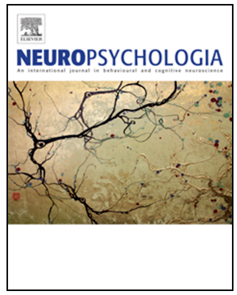

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Perceptual Training Narrows the Temporal Binding Window of Audiovisual Integration in Both Younger and Older Adults

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Highlights

- Perceptual training narrows the temporal binding window of younger and older adults
- A post-training reduction in the binding window is also observed for younger adults
- However, this reduction is not observed for older adults

Abstract

There is a growing body of evidence to suggest that multisensory processing changes with advancing age- usually in the form of an enlarged temporal binding window- with some studies linking these multisensory changes to negative clinical outcomes. Perceptual training regimes represent a promising means for enhancing the precision of multisensory integration in ageing; however, to date, the vast majority of studies examining the efficacy of multisensory perceptual learning have focused solely on healthy young adults. Here, we measured the temporal binding windows of younger and older participants before and after training on an audiovisual temporal discrimination task to assess (i) how perceptual training affected the shape of the temporal binding window and (ii) whether training effects were similar in both age groups. Our results replicated previous findings of an enlarged temporal binding window in older adults, as well as providing further evidence that both younger and older participants can improve the precision of their audiovisual timing estimation via perceptual training. We also show that this training protocol led to a narrowing of the temporal binding window associated with the sound-induced flash illusion in both age groups indicating a general refinement of audiovisual integration. However, while younger adults also displayed a general reduction in crossmodal interactions following training, this effect was not observed in the older adult group. Together, our results suggest that perceptual training narrows the temporal binding window of audiovisual integration in both younger and older adults but has less of an impact on prior expectations regarding the source of audiovisual signals in older adults.

Key words: Multisensory integration; audiovisual integration; perceptual learning; perceptual training; temporal binding window; sound-induced flash illusion

Introduction

To accurately represent the environments we inhabit, our brains must integrate relevant information from several different sensory modalities. Perhaps the most demanding aspect of this process of multisensory integration is determining whether sensory cues originate from the same external event. One strategy for performing this task is to restrict integration to cues that coincide in space and time; however, the brain must maintain a degree of tolerance for spatial and temporal discrepancies given the large differences in the physical transmission and sensory processing times between the senses (e.g. King & Palmer, 1985; Spence & Squire, 2003; Raij et al., 2010). In the temporal domain, the concept of the temporal binding window (TBW)- the time window within which sensory signals arriving from different sensory modalities are likely to be integrated into a single percept- has proven useful in understanding these tolerances. In recent years, a number of psychophysical paradigms have been developed to measure this TBW (e.g. Colonius & Diederich, 2004; Hairston et al., 2005; Navarra et al., 2005; Zampini et al., 2005; van Wassenhove, Grant & Poeppel, 2007; Setti et al., 2011; Stevenson et al., 2012; McGovern et al., 2016a) and while the ideal width of this window is context-dependent and influenced by task demands, a number of studies have reported a broader window associated with several clinical conditions (reviewed in Wallace & Stevenson, 2014).

One successful application of these psychophysical paradigms is in showing that the width of the TBW increases with advancing age (Diederich, Colonious & Schomburg, 2008; Setti et al., 2011; DeLoss, Pierce & Andersen, 2013; McGovern et al., 2014; Bedard & Barnett-Cowan, 2016). Although there is evidence that older adults could benefit from this enhanced multisensory integration when processing congruent multisensory stimuli (Laurienti et al., 2006; Peiffer et al., 2007; Diederich et al., 2008), the finding that older adults respond to a larger number of incongruent inputs has the potential to increase distractibility in this cohort, which could in turn lead to behavioural errors (Poliakoff et al., 2006). Indeed, previous research has indicated that fall-prone older adults display an enlarged TBW relative to age-matched controls, suggesting that the integration of auditory and visual stimuli with very different timings could increase the risk of falling (Setti et al., 2011). Findings such as these point to the importance of establishing interventions that could be used to narrow the TBW in older adults.

Perceptual training paradigms have proven effective in narrowing the TBW of multisensory integration in younger adults using a variety of tasks and stimuli (Powers et al., 2009; Powers et al., 2012; Stevenson et al., 2013; De Niear, Koo & Wallace, 2016; McGovern et al., 2016a; Powers et al., 2016; Horsfall, Wuerger & Meyer, 2021). For instance, Powers et al. (2009) demonstrated a robust effect of perceptual learning on an audiovisual simultaneity task such that participants could better discriminate between synchronous and asynchronous audiovisual stimuli, which in turn led to a significant narrowing of the TBW measured using the same simultaneity judgment. Building on this initial work, McGovern et al. (2016a) demonstrated that this narrowing effect from audiovisual temporal training also generalises to other tasks requiring audiovisual integration (but see Powers et al., 2016). Furthermore, this work demonstrated that temporal discrimination training not only leads to a narrowing of the TBW, but also a general reduction in the magnitude of crossmodal interactions across all temporal disparities (i.e. a reduction in the peak amplitude of the binding window). Together, these results could be explained through a Bayesian causal inference model (Kording et al., 2007) in which learning leads to both increased precision of audiovisual timing estimation and a decreased prior expectation that the stimuli originated from a common source (McGovern et al., 2016a).

Despite strong evidence showing that perceptual learning is effective at improving multisensory perception in younger adults, the literature investigating whether perceptual training can improve multisensory perception in older adults remains scarce. In the first study to address this question, Setti et al., (2014) demonstrated that five days of training on a temporal order judgement task led to a reduction in the number of trials in which older participants experienced the sound-induced flash illusion (SIFI), an audiovisual illusion in which one visual flash accompanied with two auditory tones can be perceived as multiple flashes (Shams, Kamitani & Shimojo, 2000). Setti et al. suggested that these results could be explained in terms of a narrowing of the TBW; however, the width of the binding window was not measured in this study and thus, this hypothesis still needs to be tested. Furthermore, training effects were not evident in all participants in this study, perhaps indicating some role of individual differences in multisensory learning. In a follow-up study, O’Brien, Chan and Setti (2020) trained younger and older participants on a two-interval forced choice (2-IFC) audiovisual simultaneity task for three training sessions and used the same task to the measure the TBW in pre- and post-training sessions. Their results showed a significant narrowing of the TBW for both age groups on the audiovisual simultaneity task; however, in this case, training did not impact susceptibility to the SIFI for the older adult group.

Together, these findings suggest that perceptual training can be used to narrow the TBW of audiovisual integration in older adults, although the evidence is equivocal regarding whether these training effects generalise to different contexts and/or perceptual tasks.

In the current study, we aimed to further explore whether the effects of multisensory training can transfer to other tasks that require multisensory temporal processing in both younger and older adults. Specifically, participants were required to train on a 2-IFC audiovisual simultaneity task for three days and each participant's TBW was measured before and after the training period using the SIFI (Shams et al., 2000) to establish whether training was effective in changing the shape of the binding window. To increase the likelihood that training would narrow the TBW, each training session consisted of multiple blocks of trials comprising separate staircase procedures focusing on either visual-lead or auditory-lead stimuli. Moreover, by measuring many different stimulus onset asynchronies between the audiovisual stimuli in the pre- and post-training task, the current paradigm allowed us to observe whether perceptual training was effective in reducing the width and/or the peak amplitude of the TBW and whether any of these effects are impacted by natural ageing. Finally, we also assessed whether perceptual training differentially affected the "fission" (perceiving one flash as two) and "fusion" (perceiving two flashes as one) variants of the SIFI, as previous research indicates several areas of dissociation between these phenomena, perhaps indicating that they reflect different aspects of integration (reviewed in Hirst et al., 2020).

In line with previous research (e.g. Powers et al., 2009; Setti et al., 2014; McGovern et al., 2016a), we anticipated that perceptual training would lead to a narrowing of the TBW associated with the fission illusion in younger adults and expected that this would also be observed in the older adult group. Following our previous work (McGovern et al., 2016a), we also hypothesised that training would lead to a reduction in the amplitude of the TBW, although it was less clear whether this post-training reduction in amplitude would extend to the older age group. Given previous findings reported by us (McGovern et al., 2014) and others (e.g. Watkins et al., 2007; Mishra et al., 2008) which suggest that the fission and fusion illusions reflect dissociable mechanisms of multisensory integration, it was less clear whether or not perceptual training would alter the shape of the TBW for this variant of the illusion. However, we included it in our analysis in order to expand our understanding of possible parallels and differences between the fission and fusion versions of the SIFI.

Methods

Participants

Twenty-three younger and twenty-two older participants volunteered to take part in the study. Two of the younger adults did not complete all the sessions of the experiment and their data were therefore excluded from the analysis, while two older adults had difficulty understanding one or more of the tasks and elected to withdraw from the study. This left a final sample of twenty-one younger participants (13 female, age range: 19-31, mean (median) age: 23 (22) years old, standard deviation=3.18) and twenty older participants (11 female, age range: 65-85, mean (median) age: 71 (69) years old, standard deviation=5.74). The younger participants were recruited from the student population of Trinity College Dublin and were compensated with research credits for their time. Older volunteers were community-living adults recruited through advertisements in local newspapers and community groups and were compensated for their travel expenses. Many of the older adults were part of an existing volunteer participant panel in the Multisensory Cognition Group in Trinity College Dublin and the research team used previously acquired measures of unisensory performance to recruit participants with good vision and hearing. Criteria for inclusion in the study were: normal or corrected-to-normal vision and hearing; no personal history of neurological or psychiatric illness, brain injury, abuse of substances or use of psychotropic drugs; and a minimum score of 26 on the Montreal Cognitive Assessment (MoCA). All participants were naive to the purposes of the study and provided written consent to participate.

Visual acuity in near and far ranges was measured in older participants using the SLOAN Two-Sided ETDRS Near Vision and the 4 m 200 Series Revised ETDRS charts (Precision Vision, La Salle, and Illinois, USA), respectively. Contrast sensitivity was estimated using the Pelli-Robson Contrast Sensitivity Test. All older participants included in the study showed normal acuity and contrast sensitivity for their age. Self-reported hearing was assessed by asking participants whether they had any difficulty in hearing and all participants included in the study indicated that they had no significant hearing difficulties and did not require a hearing aid. All recruitment and experimental procedures were approved by the School of Psychology Research Ethics Committee, Trinity College Dublin.

Apparatus and Stimuli

Stimulus generation and presentation were controlled by an Apple Mac Pro computer and stimuli were presented on a gamma-corrected BenQ XL2410T monitor at a refresh rate of 120 Hz and a spatial resolution of 1920 x 1080 pixels. Participants were positioned with a head support and chin rest at a distance of 57 cm from the screen. Experimental testing was conducted in a dark, windowless room in the Trinity College Institute of Neuroscience.

Stimuli were created and displayed in Matlab version 7.14 (R2012a) using Psychtoolbox (Brainard, 1997; Pelli, 1997). The visual stimulus for both the pre-/post-training measures and the training sessions was a hard-edged annulus presented at maximum luminance and displayed for 8.33 ms (a single video frame). The inner and outer edges of the annulus stimulus extended 8.5 and 10◦ from the centre of the screen, respectively. The auditory stimulus was a brief auditory tone with a frequency of 3.5 KHz, which was presented for 8.33 ms via Sennheisser HD 202 headphones at a sound pressure level of 65 dB. The relative timing of the visual and auditory stimuli was verified using a dual-channel oscilloscope.

Procedure

The experiment consisted of three successive testing sessions. In the first testing session, participants had their vision assessed (as described above), completed the MoCA, completed the pre-training measure of the TBW (via the SIFI) and completed the first training session using an audiovisual simultaneity task (see below for further details). The second day consisted of a training session, while the third day involved a training session followed by the post-training measurement of the TBW. The pre- and post-training sessions consisted of a numerosity judgement- where participants had to indicate whether a trial contained one or two flashes- which was used to measure the temporal binding windows associated with the fission and fusion variants of the SIFI. The training sessions consisted of a 2-IFC audiovisual simultaneity task, where participants had to indicate which of two audiovisual pairs were presented synchronously. The visual and auditory stimuli used for both the pre-/post-measures and the training sessions were identical (outlined in Apparatus and Stimuli); however, the timing of the stimuli and the task that participants were required to perform were different (outlined in further detail below).

Pre- and post-training measures

Before and after training, participants completed a numerosity judgement in which they had to indicate whether a trial contained one or two visual flash stimuli (see Figure 1). On each trial, the visual flash stimuli could be accompanied by one, two or no auditory beeps. Thus, there were six different conditions, representing all possible combinations of flashes and beeps. For convenience, we will subsequently refer to these conditions by an abbreviation, which relates to their veridical percept. For example, trials described as 2F1B refer to trials where two flashes were accompanied by one beep. Participants were instructed to report how many flashes they perceived while ignoring the auditory beeps, which were irrelevant to the task. Conditions known to produce the fission (1F2B) and fusion (2F1B) variants of the SIFI were randomly interleaved with unisensory (1F0B and 2F0B) and multisensory (1F1B and 2F2B) control trials, such that there were six different conditions comprising an equal number of trials. In order to provide a measure of the TBW of audiovisual integration, trials containing two flashes or two beeps were separated by one of ten stimulus onset asynchronies (SOAs; -400 ms, -200 ms, -100 ms -50 ms, -25 ms, 25 ms, 50 ms, 100 ms, 200 ms, 400 ms), where positive and negative values indicate visual-lead and auditory-lead trials, respectively. This was the case for both multisensory and unisensory trials in order to keep the number of trials equal across different conditions. Participants completed a minimum of 10 trials per SOA for each condition, yielding a minimum of 600 trials per each measure of the TBW (10 SOAs x 6 conditions x 10 repeats). Participants also collected 10 trials per SOA on a unisensory auditory version of the task, where they were required to indicate whether one or two beeps were presented. Both younger and older participants displayed close to perfect performance on this version of the task, with no differences between the age groups and very few errors overall. Pre- and post-training sessions lasted approximately 45 minutes and participants were encouraged to take breaks at regular intervals to avoid fatigue.

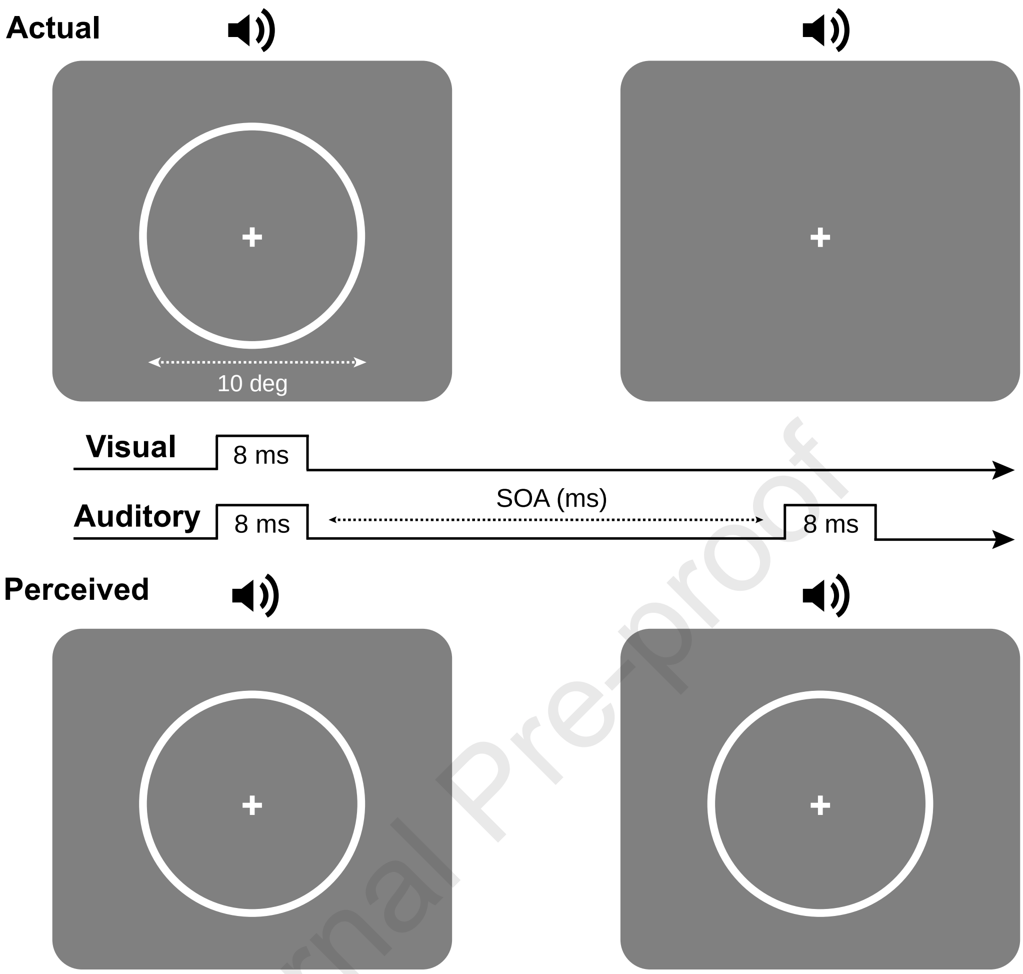


Figure 1: A schematic example of a 1F2B trial, with a positive SOA (i.e. visual lead), in which one visual flash is presented with two auditory beeps (upper part of figure) that gives rise to the perception of two flashes (lower part of the figure).

Training sessions

In each training session, participants practiced a 2-IFC audiovisual simultaneity task in which they were required to judge which of two audiovisual pairs were presented synchronously. This task used the same stimuli as in the pre- and post-training measures but consisted of two intervals and tested participants ability to assess the relative timing of the stimuli as opposed to performing a numerosity judgement. Participants completed five separate runs in each training session, which consisted of two interleaved staircases (40 trials each). The staircases were used to control the SOA of the asynchronous audiovisual pair and varied according to a 3-down, 1-up rule converging on an accuracy level of 79%. One of the two interleaved staircases only presented audiovisual pairs in which the visual stimulus preceded the auditory stimulus, while the other staircase only presented audiovisual stimuli in which the visual stimulus followed the auditory stimulus. The presentation order of the synchronous and asynchronous intervals was chosen at random on each trial with the two intervals separated by 1000 ms. As for the pre- and post-training sessions, the stimuli consisted of annulus stimuli and auditory beeps presented for a duration of 8.33 ms.

Feedback was presented on a trial-by-trial basis in the form of high and low pitch tones, which indicated correct and incorrect responses, respectively. Discrimination thresholds were calculated as the mean of the last four reversals of each staircase and participants completed ten staircases (5 auditory-lead and 5 visual-lead) of 40 trials in each training session (400 trials per training session). Average daily thresholds for each participant were calculated as the mean of the ten threshold measurements.

Data analysis

To examine training effects on audiovisual integration, we compared performance on the numerosity task before and after training by examining the proportion of illusory responses across all SOAs in the 1F2B (fission) and 2F1B (fusion) conditions. Statistical analyses were conducted on these data using mixed-model ANOVAs to analyse the effects of age and training on the proportion of illusory responses for both conditions. All statistical analyses were conducted in JASP (JASP team, 2020).

To further quantify the effects of training on the shape of the TBW measured for 1F2B and 2F1B trials, a curve-fitting procedure was employed to establish estimates of the width and peak amplitude of the TBW for both the group-averaged and individual pre- and post-training data. While a Gaussian distribution was judged to provide a good approximation of the TBW for the 2F1B trials, the asymmetric nature of the TBW associated with 1F2B trials required that a half-normal distribution was fitted to each side of the TBW separately with the estimated parameter values averaged (see Stevenson et al., 2012 for a similar approach). For both of these curve fitting procedures, the standard deviation and amplitude were left as free parameters to provide an estimate of the width and peak amplitude of the TBW, respectively. To ensure that the parameter values derived from the curve fits to the individual data provided meaningful estimates of the TBW, curve fits that produced an R^2 of less than

50% were excluded from this analysis. If the curve fit to either the pre-training or post-training data fell below this threshold, the data for this participant was removed from this part of the analysis. This led to the removal of data from five older participants and two younger participants for the analysis of the 1F2B (fission) trials, and the removal of data from three younger participants and four older participants in the analysis of the 2F1B (fusion) trials. For this analysis, outliers were defined as parameter estimates with a learning ratio (pre-training parameter estimate/post-training parameter estimate) more than 2.5 standard deviations from the mean value and this led to the removal of one estimate of the peak amplitude from the younger age group and one estimate of the standard deviation from the older group, both for the 1F2B (fission) analysis. Data from all participants in the study were included in the group-averaged analyses and plots.

Following McGovern et al. (2014), the data from 2F1B trials was baseline corrected to take into account performance on the unisensory 2F0B trials. This baseline correction was applied to control for any differences in visual temporal acuity between younger and older adults. Specifically, each participant's data were normalised by their accuracy level in the 2F1B trials at each SOA to better reflect the proportion of fusion reports that arose due to multisensory interactions driven by the presence of the auditory tone as opposed to poorer temporal resolution.

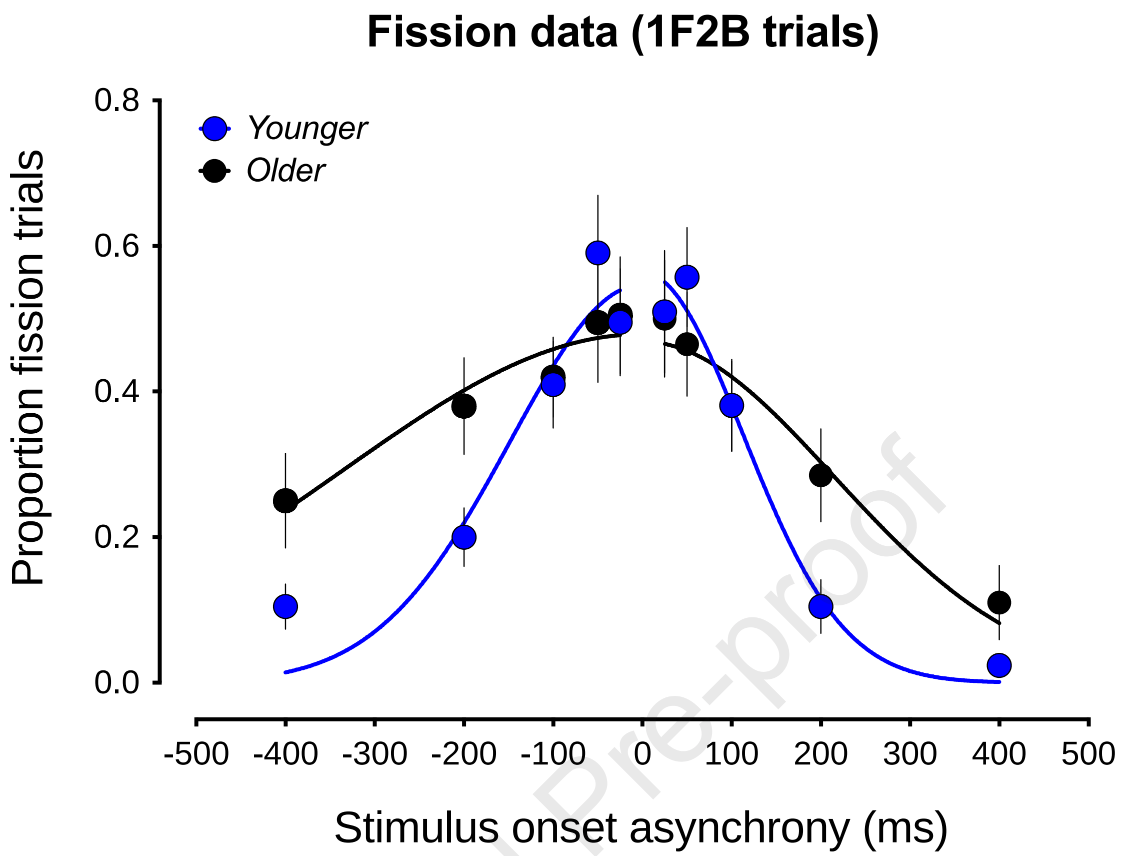
Results

Age-related differences in the width of the temporal binding window for the fission, but not the fusion, illusion prior to training

In keeping with previous findings (Setti et al., 2011; McGovern et al., 2014), the measures of the TBW taken before perceptual training commenced indicated that older adults displayed a wider TBW than their younger counterparts for the fission illusion (Figure 2a). A mixed-model 2 (age group) x 10 (SOA) ANOVA conducted on the 1F2B trials revealed a significant main effect of SOA ($F(9, 351) = 25.18$, $p<0.001$, partial $\eta^2 = 0.392$) and a significant group x SOA interaction ($F(9, 351) = 2.4$, $p = 0.014$, partial $\eta^2 = 0.057$), indicating that the temporal limits of the fission illusion differed between the younger and older adult groups. Unlike our previous work, there was no main effect of age group on the proportion of trials in which participants experienced the fission illusion ($F(1, 39) = 0.41$, $p = 0.52$, partial $\eta^2 = 0.011$). This discrepancy is likely explained by the fact that the current study included more trials with shorter SOAs, where younger participants experience a marginally stronger illusory effect relative to the older group (see Figure 2a). In line with this, the results of the half-normal distribution fits to the group-averaged data indicated that while the peak amplitude of the TBW was higher for younger participants relative to their older counterparts (0.65 vs 0.47), the width of the TBW- estimated here as the standard deviation of the Gaussian curve fit- for older adults was more than twice that of the younger group (130 ms vs 276 ms). Broadly in keeping with these findings from the curve fits to the group-averaged data, the individual curve fit analysis revealed that while younger adults had a significantly narrower TBW than their older counterparts before training commenced ($t(34) = 2.2$, p = 0.036, Cohen's $d = 0.74$), the difference in the peak amplitude of the binding windows between the two age groups was not statistically significant ($t(34) = 0.012$, p = 0.99, Cohen's $d = 0.004$).

In contrast to the analysis of the 1F2B trials, the curve fitting analysis to the 2F1B trials revealed that there was no significant difference in either the peak amplitude ($t(35) = 0.67$, p = 0.51, Cohen's $d = 0.22$) or the width of the TBW (t(35) = 0.083, p = 0.93, Cohen's $d = 0.027$) associated with the fusion illusion between the two age groups. The curve fits to the group-averaged data also suggested that there was little evidence of an age-related difference in the peak amplitude (Younger: 0.33, Older: 0.32) or the width (Younger: 78 ms, Older: 93 ms) of the fusion TBW (Figure 2b). These findings are broadly consistent with our previous studies which showed no age-related differences in susceptibility to the fusion illusion between younger and older adults (McGovern et al., 2014); although one difference between the age groups in the current data is that while the younger adult group display a roughly symmetric pattern of susceptibility for auditory- and visual-lead conditions, older adults appear to be more prone to experiencing the fusion illusion in auditory-lead conditions (negative SOAs).

a.


Fission data (1F2B trials)
Younger
Older
Proportion fission trials
0.0
0.2
0.4
0.6
0.8
-500 -400 -300 -200 -100 0 100 200 300 400 500
Stimulus onset asynchrony (ms)

b.

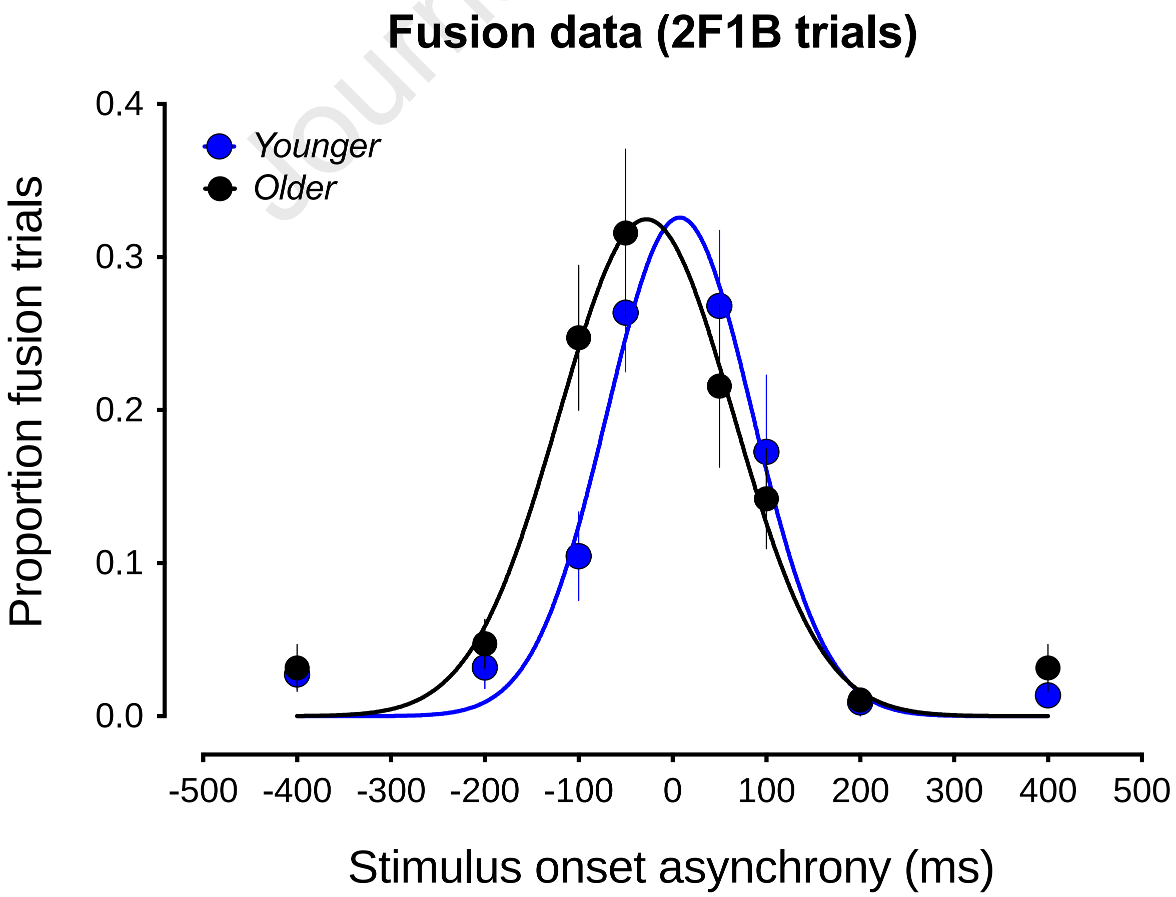

Fusion data (2F1B trials)
Younger
Older
Proportion fusion trials
0.0
0.1
0.2
0.3
0.4
-500 -400 -300 -200 -100 0 100 200 300 400 500
Stimulus onset asynchrony (ms)

Figure 2: Mean proportion of illusion responses in the fission (1F2B) and fusion (2F1b) conditions as a function of stimulus onset asynchrony (positive and negative values indicating visual- and auditory-lead trials, respectively) for younger and older adults. (a) In the fission condition, older adults display comparable performance to younger adults for short SOAs. However, whereas the illusion becomes less frequent for younger adults at longer SOAs, older adults still report the illusion on a significant proportion of trials for the longest SOAs (±400 ms). (b) In the fusion condition, younger and older adults display similar performance for most SOAs, albeit older adults are more likely to experience the fusion illusion in auditory-lead (negative SOAs) than visual-lead (positive SOAs) conditions, while the pattern of illusory responses is roughly symmetric for younger adults. Solid lines show best-fitting half-normal and Gaussian distributions to the fission and fusion data points, respectively.

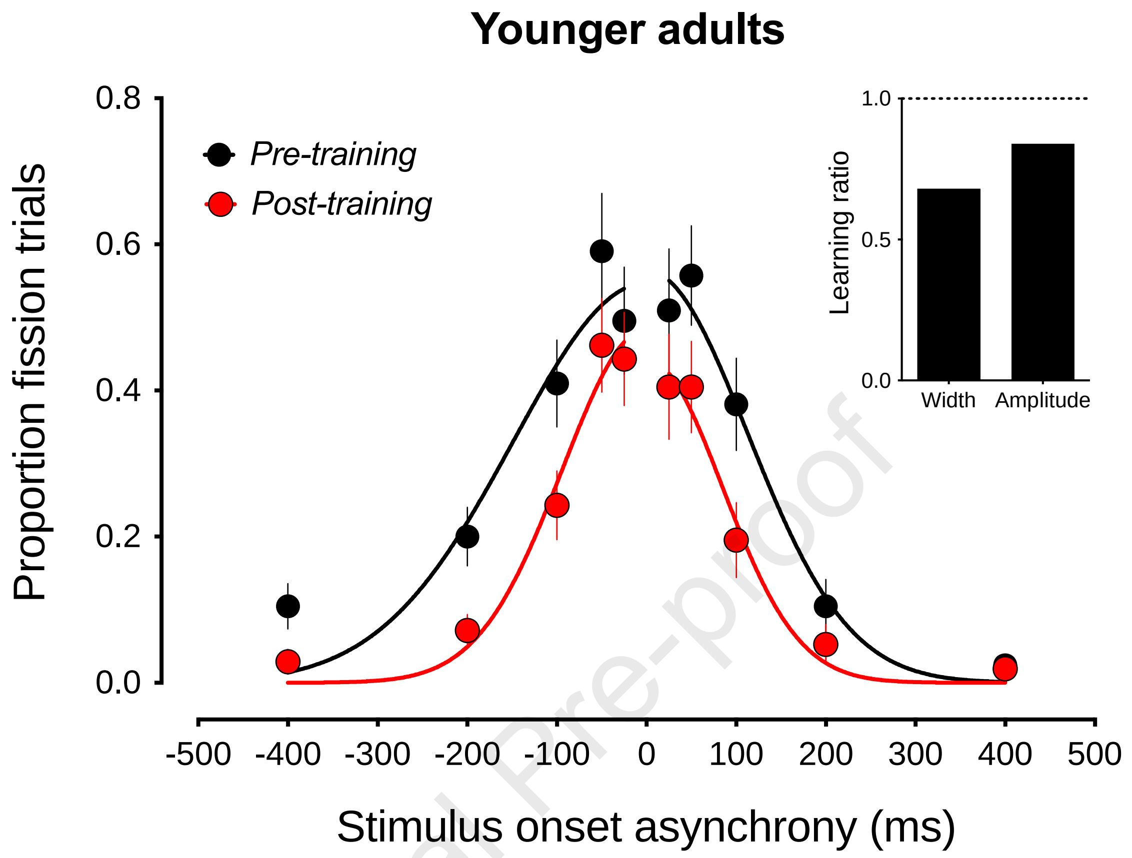
Audiovisual simultaneity training leads to a narrowing of the temporal binding window associated with the fission illusion for both young and older adults

Following the initial measurement of the TBW via the SIFI, participants engaged in three sessions of training on a 2IFC simultaneity task, in which they had to indicate which of two audiovisual pairs were simultaneous on a given trial. Consistent with previous studies (Powers et al., 2009, 2012; McGovern et al., 2016a; O'Brien et al., 2020), participants showed significant improvements in audiovisual simultaneity discrimination following training, with younger and older adults showing threshold reductions of approximately 30% and 40%, respectively. This improvement from the first to the third training session was statistically significant for both the younger (pre: 194 ms post: 140 ms; $t(20) = 4.93$, $p < 0.001$, Cohen's $d = 1.12$) and older (pre: 309 ms, post: 180 ms; $t(19) = 7.7$, $p < 0.001$, Cohen's $d = 1.07$) age groups.

Following training, participants again completed the numerosity judgement task so that we could estimate the impact of perceptual training on the TBW associated with the SIFI and a repeated measures ANOVA was used to analyse the effects of session (pre vs. post) and SOA on the TBW for each age group (two ANOVAs in total, one per age group). For both age groups there was a significant main effect of session such that, overall, participants were less susceptible to the SIFI post training (Younger: $F(1, 20) = 22.1$, $p < 0.001$, partial $\eta^2 = 0.525$; Older: $F(1, 19) = 15.01$, $p = 0.001$, partial $\eta^2 = 0.441$; see Figure 3). There was a significant session x SOA interaction for the older participant group ($F(9, 171) = 2.36$, $p = 0.015$, partial $\eta^2 = 0.11$), although this interaction was not statistically significant for the younger participant group ($F(9, 180) = 1.86$, $p = 0.06$, partial $\eta^2 = 0.085$).

The significant interaction between SOA and pre/post-training sessions observed in older adults suggests that the TBW narrowed in this cohort following training. To assess whether this was the case, we fitted a half-normal distribution curve separately to the negative and positive SOA conditions from the pre- and post-training sessions for both the younger and older groups and averaged the estimated standard deviation values to provide an overall estimate of the width of the TBW. We first conducted this analysis on the group-averaged data (see Figure 3) and found that both the younger and older age groups demonstrated a narrowing of the TBW after training (Younger: 130 ms to 89 ms; Older: 276 ms to 129 ms). Next, we fitted the half-normal distribution to each participant's pre- and post-training data, which led to individual measures of the TBW and allowed us to assess whether these trends observed in the group-averaged data were statistically significant (see Supplementary Figure 1 for individual curve fits). This analysis revealed that both groups displayed a significant narrowing of the TBW following training (Younger: $t(18) = 3.23$, $p = 0.005$, Cohen's $d = 0.74$; Older: $t(13) = 3.84$, $p = 0.002$, Cohen's $d = 1.03$). Interestingly, while this analysis also revealed a significant post-reduction in the peak amplitude of the binding window for younger adults $t(17) = 2.57$, $p = 0.02$, Cohen's $d = 0.61$), a similar effect was not observed in the older adult group ($t(14) = 0.04$, $p = 0.97$, Cohen's $d = 0.01$). Similar effects were also observed in the group-averaged fits (see Figure 3), such that there was a notable post-training reduction in the peak amplitude for younger participants (0.65 to 0.55), but this was not observed for older adults (0.47 to 0.46).

a.


Younger adults
Proportion fission trials
0.8
0.6
0.4
0.2
0.0
Pre-training
Post-training
Learning ratio
1.0
0.5
0.0
Width
Amplitude
-500 -400 -300 -200 -100 0 100 200 300 400 500
Stimulus onset asynchrony (ms)

b.

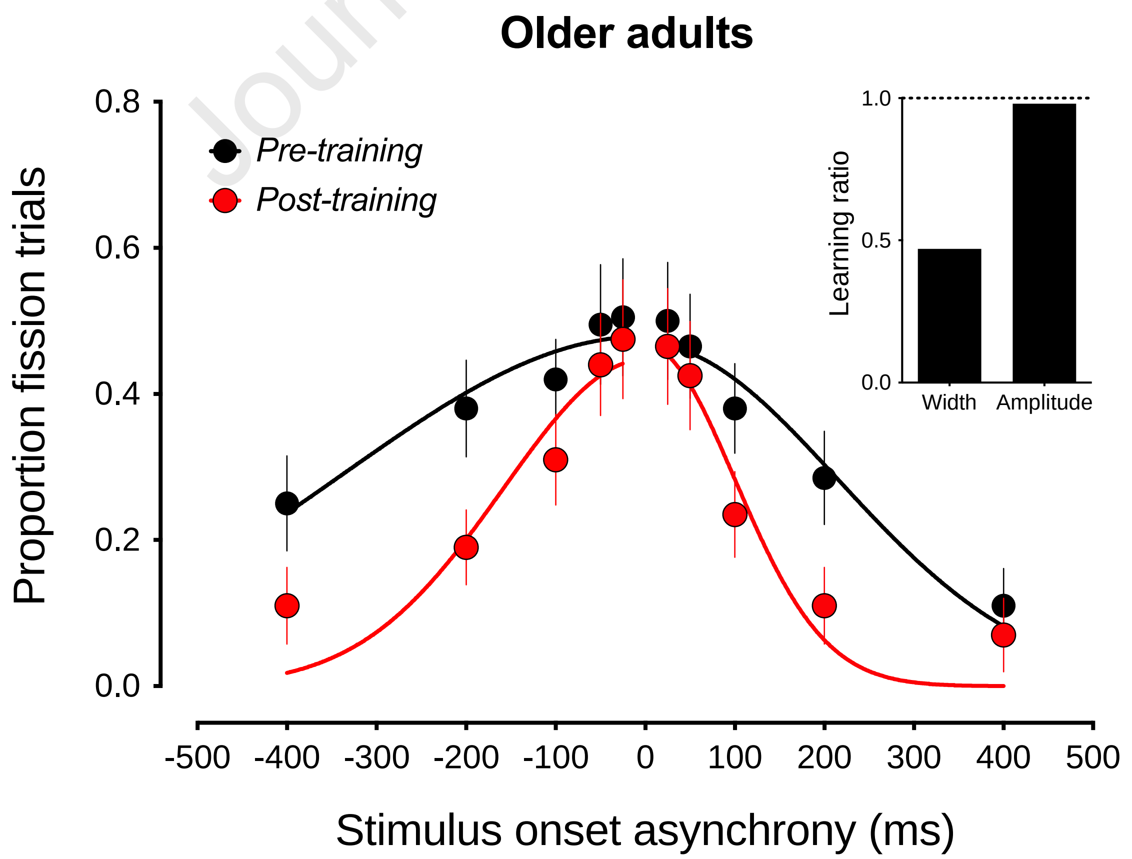

Older adults
Proportion fission trials
0.8
0.6
0.4
0.2
0.0
Pre-training
Post-training
Learning ratio
1.0
0.5
0.0
Width
Amplitude
-500 -400 -300 -200 -100 0 100 200 300 400 500
Stimulus onset asynchrony (ms)

Figure 3: Training effects on the temporal binding window (TBW) associated with the fission illusion for younger and older adults. (a) For younger adults, perceptual training on audiovisual simultaneity task led to narrowing of the TBW- as estimated by the standard deviation of the best fitting half-normal distributions to the pre- and post-training data- as well as a general reduction in the number of illusory responses across all SOAs. The inset provides a summary of these training effects in the form of learning ratios in which the width (standard deviation) and peak amplitude of the best fitting curves from the post-training data are divided by those from the pre-training data. Here, a value of 1 indicates no effect of training while values less than one indicate a reduction width/amplitude following training. (b) Older adults also display a narrowing of the TBW following training on the audiovisual simultaneity task. Unlike the data from the younger adult group, however, no difference in the peak amplitude was observed following training. This is reflected in the inset of the panel where the leaning ratio for the width of the window is approximately 0.5 indicating a halving of window width following training, while the learning ratio for the peak amplitude is close to 1 indicating no change.

Effects of perceptual training on the temporal binding window associated with the fusion SIFI

We next examined what impact perceptual training had on the TBW associated with the fusion effect for both age groups. This analysis revealed a significant main effect of session for both age groups such that each group displayed reduced susceptibility to the fusion SIFI following training (Younger: $F(1, 20) = 12.87$, p = 0.002, partial $\eta^2 = 0.392$; Older: $F(1, 19) = 9.52$, p = 0.006, partial $\eta^2 = 0.334$). In a reversal of the results for the fission illusion, there was a significant session x SOA interaction for the younger group ($F(7, 140) = 3.16$, p = 0.004, partial $\eta^2 = 0.136$), but this interaction was not statistically significant for the older adult group ($F(7, 133) = 1.3$, p = 0.26, partial $\eta^2 = 0.06$). In line with this, the individual curve fit analysis revealed a significant narrowing of the TBW associated with the fusion illusion for younger participants ($t(16) = 2.63$, p = 0.02, Cohen's $d = 0.64$), but not for older adults ($t(15) = 0.14$, p = 0.89, Cohen's $d = 0.04$; see Supplementary Figure 2 for individual curve fits). Meanwhile, neither age group displayed a significant reduction in the peak amplitude of the fusion TBW following training (Younger: $t(16) = 2.09$, p = 0.053, Cohen's $d = 0.51$; Older: $t(15) = 1.31$, p = 0.21, Cohen's $d = 0.33$), despite the group-averaged fits suggesting that there may be a training-related reduction in amplitude for both the younger (pre: 0.33, post: 0.23) and older (pre: 0.33, post: 0.24) groups (see Figure 4).

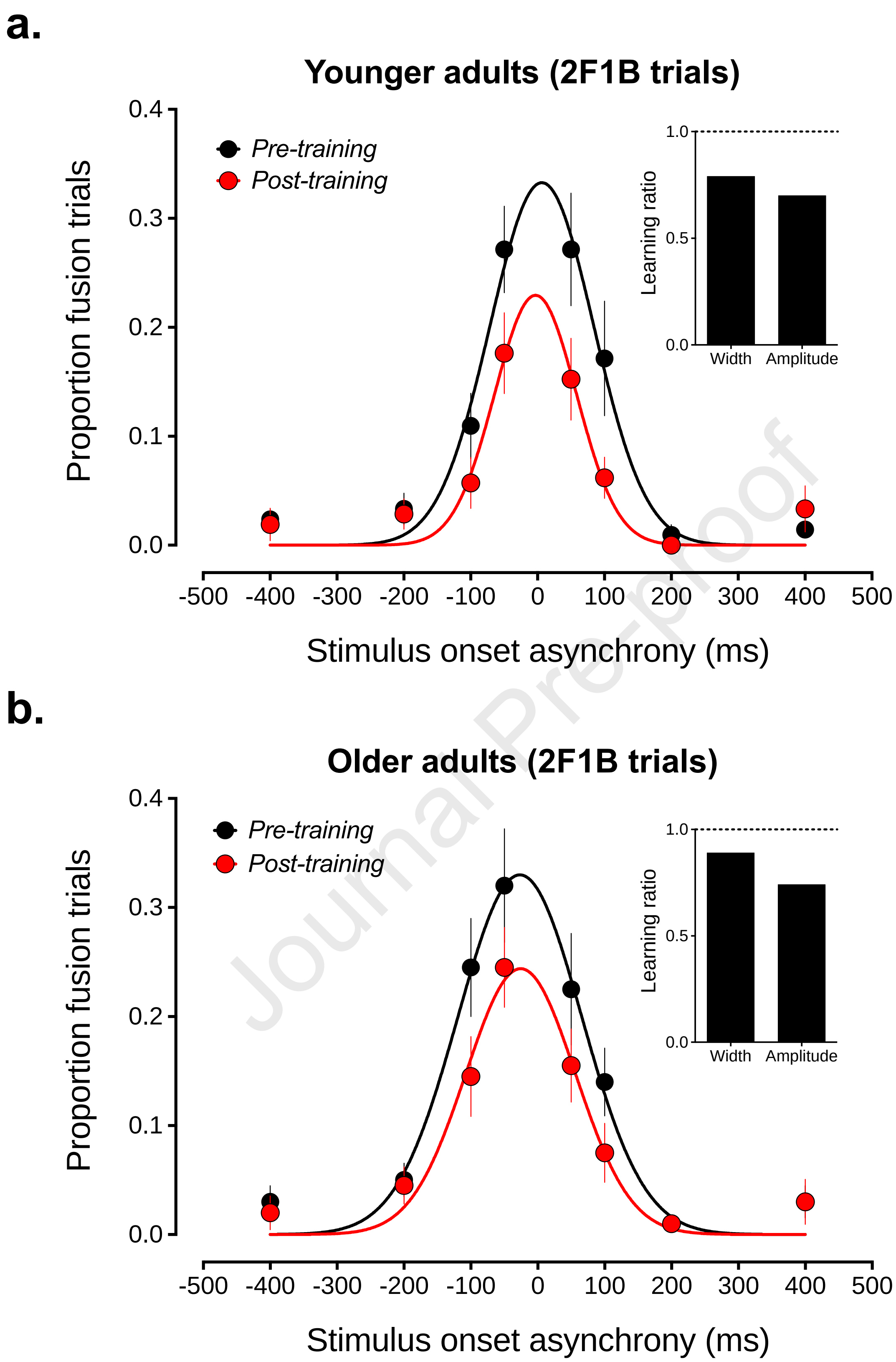


Figure 4: Training effects on the temporal binding window (TBW) associated with the fusion illusion for younger and older adults. (a) For younger adults, perceptual training on audiovisual simultaneity task led to both a narrowing of the TBW and a general reduction in the number of illusory responses across all SOAs. The inset provides a summary of these training effects in the form of learning ratios in which the width (standard deviation) and peak amplitude of the best fitting curves from the post-training data are divided by

those from the pre-training data. Here, a value of 1 indicates no effect of training while values less than one indicate a reduction width/amplitude following training. (b) Older adults displayed a very similar pattern of training effects with both a narrowing of TBW and a general reduction in crossmodal interactions across all SOAs observed after training.

Discussion

There is a growing body of evidence to suggest that natural ageing impacts on multisensory integration, with these age-related effects often taking the form of an expanded temporal binding window. Perceptual training with multisensory stimuli represents a potential avenue to enhance the precision of temporal multisensory perception in older adults, which may have important consequences for lowering risk of clinical outcomes such as fall risk (Setti et al., 2014), mild cognitive impairment (Chan et al., 2015) and promoting general cognitive health (Hernandez et al, 2019). However, the existing literature is equivocal as to whether multisensory perceptual learning leads to a general improvement in audiovisual integration or whether these effects are specific to the trained task and/or stimulus. Here, we provide evidence of a generalised improvement in audiovisual integration following training on an audiovisual temporal simultaneity discrimination task, which led to a narrowing of the TBW associated with the SIFI in both younger and older adults. While younger adults also displayed a general reduction in fission SIFI susceptibility across most SOA conditions following training, this was not the case for the older adults indicating that these training effects are, to some extent, age dependent. Our results also revealed a different pattern of training-related effects on the TBWs associated with the fission and fusion variants of the SIFI providing further evidence that these two illusions may reflect different underlying mechanisms.

While many studies have examined the effects of perceptual training on multisensory integration in younger adults, to the authors' knowledge only two previous studies have addressed whether multisensory perceptual learning is effective in older adults (Setti et al., 2014; O'Brien et al., 2020). In the first of these studies, Setti et al. (2014) demonstrated that a subset of older adults could improve their performance in discriminating the temporal order of auditory and visual stimuli with training and that these improvements were associated with reduced susceptibility to the fission SIFI. In contrast, a follow-up study showed that although older adults improved their performance on an audiovisual simultaneity task through training, these effects did not generalise to changes in susceptibility of the SIFI (O'Brien et al., 2020). The current results are more in keeping with those of Setti et al. (2014) in that the older adults in our study improved their audiovisual temporal discrimination abilities, but also showed reduced susceptibility to the fission SIFI after training. However, it should be pointed out that this reduced susceptibility was only observed for longer SOA conditions, with no effect observed for shorter SOAs (see Figure 3b). This may be the reason for the difference between the current results and those of O'Brien et al.; while the current study included ten SOA conditions, extending to relatively large time differences (i.e. 400 ms), O'Brien et al. used four SOAs extending out to 230 ms. Indeed, it is interesting to note that older adults in the study by O'Brien et al. also reported fewer illusory responses for the 230 ms SOA condition following training, in contrast to the findings for shorter SOAs.

The current results point to a general improvement in audiovisual integration following multisensory temporal training in both younger and older adults; however, it should be noted that the conditions that lead to generalised improvement following multisensory training still require elucidation. For example, while a number of studies have shown that the effects of perceptual learning can transfer from one multisensory task or context to another (Setti et al., 2014; McGovern et al., 2016a; Surig et al., 2018; Zerr et al., 2019), other studies have failed to do so (Powers et al., 2016; O'Brien et al., 2020; Horsfall et al., 2021). What might contribute to these differences? One key methodological difference between these studies that could explain whether transfer is observed or not is the difficulty of the training task, with previous research suggesting that high task difficulty is important for driving improvements in audiovisual temporal processing (De Niear et al., 2016). Thus, it may be that challenging training protocols are more likely to yield generalised improvements in audiovisual integration. In line with this view, most of the studies that observed transfer of multisensory learning (Setti et al., 2014; McGovern et al., 2016a; Surig et al., 2018) employed adaptive threshold measurement techniques (i.e. staircase or Quest procedures) in their training protocols, in an effort to calibrate task difficulty to each individual's performance level, while those that observed specific training-related improvements did not (Powers et al., 2016; O'Brien et al., 2020; Horsfall et al., 2021). A further innovation employed in the current study was the use of two interleaved staircases separately targeting the visual- and auditory-lead sides of the TBW. The reason for this inclusion was that some previous research has shown that the visual-lead side of TBW is more malleable (e.g. Powers et al., 2009) and by specifically targeting the auditory-lead side of the window, we hoped for a more balanced narrowing of the binding window. This approach appears to have been successful with both younger and older adults showing an approximately symmetric narrowing of the TBW following training.

The training-related effects observed in younger adults on fission susceptibility replicate those of an earlier study, in which audiovisual simultaneity training not only led to a narrowing of the TBW but also a general reduction in crossmodal interactions (in the form of a reduced ventriloquist effect across all tested SOAs; McGovern et al., 2016a). In McGovern et al. (2016a), these dual learning effects were explained in terms of a Bayesian casual inference model, where training led to improved audiovisual timing estimation (narrowing) and also a decreased prior expectation that auditory and visual stimuli relate to a common source (amplitude reduction). If we apply a similar rationale to explain the current results, two age-related effects of interest emerge. First, while our results show that older adults display a much wider TBW to younger adults prior to training, there was no age difference in the peak amplitude of the binding windows. This suggests that younger and adults share similar *a priori* beliefs regarding the source of audiovisual signals and is in keeping with two recent studies that also found no age-related differences in audiovisual binding tendency (Jones et al., 2019; Park, Nannt & Kayser, 2021). Second, while the peak amplitude of the binding window reduced for younger adults following training in the current study, this was not the case for older adults. This finding suggests differences in the way the two age groups incorporate the statistics of previous audiovisual stimulation to update their prior expectations that auditory and visual stimuli relate to a common source. One potential reason for this age difference is that, due to the TBW being wider in older adults, this group are exposed to fewer obvious examples of asynchronous audiovisual input providing less opportunity for their perceptual priors to change over the course of the experiment. Future research should investigate whether exposure to multisensory stimuli with larger time differences are capable of changing prior expectations in older adults or whether a lifetime of experience with audiovisual input has acted to solidify *a priori* beliefs regarding the source of these stimuli.

While a number of studies have provided evidence to suggest that older adults display an enlarged TBW relative to younger adults, to our knowledge this is the first study to quantify this difference through a curve-fitting procedure. Before training, older adults had a TBW that was more than twice the size of that in their younger counterparts (270 vs 127 ms). However, one question that remains is why exactly older adults have a wider TBW. In a recent review, Jones & Noppeney (2021) suggest that multiple factors could lead to an increased tendency to integrate sensory signals. Within the context of a Bayesian inference framework, the authors suggest that age-related differences in the likelihood (unisensory signal reliability), prior knowledge (expectations and attention), cost function (decision-making strategy) or even the inference process itself could impact on the degree to which participants integrate/segregate sensory information. Indeed, previous research by us (McGovern et al., 2016a) and others (Rohe & Noppeney, 2015; Cao et al., 2019) indicates that the reliability of sensory signals plays a key role in the shape of the TBW suggesting that age-related deficiencies in temporal perception (e.g. Humes et al., 2009; Ulbrich et al., 2009; de Boer-Schellekens & Vroomen, 2014) may be the key factor underlying a wider TBW in older adults. However, age-related differences in selective attention have also been reported (e.g. Verhaeghen & Cerella, 2002; Andrés et al., 2006; Bugg et al., 2007), while there is ample evidence to suggest that older adults adopt different decision criteria than younger adults for some perceptual decisions (e.g. Ratcliff et al., 2006; Dully et al., 2018; McGovern et al., 2018; Theisen et al., 2021). Despite this, the available evidence suggests that we continue to benefit from combining multisensory cues as we age (Brooks et al., 2015; Jones et al., 2019; Park et al., 2020) indicating that older adults do perform Bayesian causal inference and reliability-weighted integration in a similar fashion to younger adults (Jones & Noppeney, 2021). To further narrow down the potential sources of wider TBWs in older adults, future studies could employ a 2-IFC version of the SIFI task (see Buergers & Noppeney, 2022), which are less susceptible to decision-level biases thereby reducing their influence on the size of the TBW; however, it should be noted that a previous study employing a signal detection theory framework indicated that the age differences observed in the SIFI were primarily the result of reduced perceptual sensitivity as opposed to changes in decision criteria (McGovern et al., 2014). Additionally, further research could look to titrate unisensory temporal performance between younger and older participants before performing the SIFI to assess how much of the difference in the size of the TBW between the age groups is accounted for by the reliability of unisensory input and whether there is still a difference when this factor is controlled.

While this study sought to reduce the width of the TBW in older adults through training, a worthwhile question to consider is whether a narrower TBW necessarily translates to better outcomes in older individuals. On the one hand, it is possible that the width of the TBW increases in older adults in order to maximise on multisensory signals and compensate for unisensory decline (e.g. Hirst et al., 2019). However, in general, wider TBWs in ageing have been associated with a number of negative clinical outcomes, including falls risk (Setti et al., 2011), mild cognitive impairment (Chan et al., 2015) and a faster rate of cognitive decline (Hirst et al., 2022). In line with these findings, we speculate that a widening of the TBW may be an adaptive process (due in part to unisensory changes) with maladaptive consequences. Thus, we interpret a widening of the TBW as reflecting less “precise” multisensory integration and suggest that reducing the width of the TBW in older adults may lead to more efficient processing of multisensory information. However, future studies should evaluate whether training-related changes to the TBW translate into better clinical outcomes for older adults.

Audiovisual simultaneity training led to different training-related effects on susceptibility to the fission and fusion illusions. For example, while older adults experienced a narrowing of the TBW for the fission illusion following training, this was not the case for the fusion illusion. These differences between the properties of the fission and fusion illusions add to a growing literature suggesting that, despite the phenomenological similarities, the two illusion variants may reflect dissociable mechanisms of audiovisual integration (Watkins et al., 2007; Mishra et al., 2008; Bolognini et al., 2011; McGovern et al., 2014; Chen et al., 2017; reviewed in Hirst et al., 2020). For instance, Chen et al. (2017) showed that while the fission illusion was larger when visual stimuli were presented in the peripheral visual field relative to foveal presentation, the opposite pattern of results was observed for the fusion illusion. An analysis based on signal detection theory revealed that while the fission results emerged due to a combination of reduced stimulus discriminability and a shift in decision criterion, the fusion results were fully explainable in terms of a criterion shift indicating that the fusion illusion is likely the result of decision bias as opposed to perceptual bias (Chen et al., 2017). The current results are broadly in line with this proposal in that perceptual training had a weaker effect on the width of the TBW than the peak amplitude of the fusion data for both younger and older adults, in contrast to the effects of training on the fission SIFI which appeared to have a larger effect on the width of the TBW.

To summarise, our results suggest that multisensory perceptual learning can produce generalised improvements in audiovisual temporal processing in both younger and older adults. While a hallmark of perceptual learning is that the effects are typically highly specific to the trained task and stimulus properties (e.g. Fiorentini & Berardi, 1980; Karni & Sagi, 1991; Poggio et al., 1992), these findings add to the recent literature showing that the effects of perceptual learning can generalise to different tasks both within (e.g. Zhang et al., 2010; McGovern et al. 2012; Green et al., 2015) and across different sensory modalities (Alais & Cass, 2010; Barakat et al., 2015; McGovern et al., 2016b) in certain contexts. Moreover, our findings provide further evidence that older adults retain the capacity to improve their perception through perceptual training (see also Bower & Andersen, 2012; McKendrick & Battista, 2013; DeLoss et al., 2015) highlighting a potential clinical utility of multisensory learning.

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