AGE-RELATED ALTERATIONS IN AUDIOVISUAL INTEGRATION:  
A BRIEF OVERVIEW

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Population ageing—a global social issue—is one of the principal challenges of the future, at least in the next few decades. Because dysfunctions arise in auditory sensory processing and visual sensory processing during healthy ageing, the function of audiovisual integration (AVI), the process of integrating auditory and visual information to correctly perceive the external environment, is also considerably altered throughout one’s lifespan. Some studies have suggested the application of multisensory perception in developing rehabilitation methods for elderly adults. Therefore, it is crucial to understand what changes occur and how the ageing brain compensates for these changes. However, because of the inherent complexity of unisensory perceptions and multisensory integration, thus far, there have been no systematic investigations on this matter. To shed light on the basic mechanisms involved in the influence of age on AVI, this comprehensive literature review summarizes the current behavioural and neural studies on AVI in ageing and discusses directions for future investigation.

Key words: audiovisual integration, ageing, dysfunction, behavioural, neuroimaging

INTRODUCTION

Regarding daily activities, when elderly and younger adults are given the same command, for example, ‘raise your right hand,’ ‘turn to the left,’ ‘read the word presented on the screen,’ or ‘discriminate which word emerges first in an auditory test,’

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elderly adults often perform tasks slower than younger adults, and they are worse at reading words and lip-reading consonants. In addition, elderly adults may soliloquize by themselves, saying things such as ‘I am not as smart as I used to be’ or ‘I feel increasingly worse and always forget what I just heard’. It is important to understand what happens to their cognitive system and what leads to changes in their executive functions with ageing.

It is now well recognized that ageing is accompanied by various changes in brain information processing that lead to functional decline, including sound localization (Abel et al., 2000; Cui et al., 2010), flash counting (Setti et al., 2011; Stapleton et al., 2014), and temporal order judgement for multimodal stimuli (Fiacconi et al., 2013; Newell, 2012; Poliakoff et al., 2006), or unimodal stimuli (Craig et al., 2010). These findings support the perspective that the decline in temporal processing due to a slowing in cognitive processing partially. Additionally, abilities related to high level cognition are also affected extensively, including speech perception (Babkoff & Fostick, 2017; Dey & Sommers, 2015; Gregoryjohnson, 2014) and object recognition deficits (Pilz et al., 2011). All these alterations due to ageing seriously hinder elderly adults’ daily lives. However, the human brain retains some plasticity even later in life (Anguera et al., 2013; Gutchess, 2014; Mozolic et al., 2011; Yang et al., 2018).

Some studies have even indicated that audiovisual integration (AVI) in elderly adults is higher than that in younger adults behaviourally (Laurienti et al., 2006; Peiffer et al., 2007; Wu et al., 2012), and these studies predicted that AVI may be a compensatory mechanism for functional decline. Diaconescu et al. (2013) reported that a distinct network of posterior parietal (PP) and medial prefrontal (MP) sources were recruited in elderly adults when response to cross-modal stimuli compared to unimodal stimuli (Diaconescu et al., 2013). Recently, Ren et al. (2018) also found significant AVI effect was elicited in an established visual processing brain region (the occipital cortex) in elderly adults but not in younger, which indicated that compensatory phenomena occurred to compensate for the decline in neurological function (Ren et al., 2018). And their following ‘audio-visual perceptual training experiment’ in elderly adults showed an enhanced P300 amplitude in elderly adults after training, which highlights the robust malleability of the ageing brain (Yang et al., 2018). In addition, to improve the quality of life of elderly people, numerous researchers have developed cognitive training games, and the participants in these games obtained noticeable cognitive gains using auditory or visual signals (Anguera et al., 2013; Toril et al., 2016). These findings confirmed that the perceptual ability of aged subjects could be improved through audiovisual intervention training (Anguera et al., 2013; Lee et al., 2020; Toril et al., 2016; Yang et al., 2018).

However, using the similar analysis, contrasting results were also reported: younger adults have much higher AVI than elderly adults (Ren et al., 2016; Stephen et al., 2010; Tye-Murray et al., 2010). Given that there are a limited number of studies focusing on AVI in ageing presently, there is insufficient evidence to clarify the mechanism of age-related AVI. However, clarifying the mechanism of AVI is helpful not only for understanding the deleterious effects of ageing on cognitive function but also for enhancing theoretical knowledge to develop cognitive training methods for maintaining
elderly adults’ independence and quality of life (Freiherr et al., 2013; Mozolic et al., 2011). Therefore, neurologists have used many research tools to clarify these mysteries. Over the last few decades, we have witnessed major advances in research technology in neuroscience, including computed tomography (CT), magnetoencephalography (MEG), electroencephalography (EEG), magnetic resonance imaging (MRI), positron emission tomography (PET), and transcranial magnetic stimulation (TMS). These technologies allow researchers to better observe the electrical and metabolic activity of the healthy human brain in vivo with non-invasive techniques (Gazzaniga et al., 2008), but work combining the temporal and spatial resolutions of these technologies is in the infant stage, and we are still squinting in the dark to develop ways to uncover the mysteries of brain.

This paper reviews studies on age-related alterations in AVI. All of these investigations used in vivo detection technology, such as MEG, EEG, and MRI. The first section describes the concept of AVI and the processing regions in which such integration occurs. The section that follows discusses the behavioural changes that accompany ageing, including changes in response times, AVI effect, and time window of AVI, that is, the time interval between the occurrence of AVI. The third section focuses on the changes observed in neuroimaging results from elderly adults compared with younger adults, and the final section discusses directions for future research. This literature indicates that as a complementary mechanism, AVI may be enhanced in elderly adults compared with younger adults and that elderly adults may recruit special brain areas or reduce hemispheric specialization to compensate for dysfunction in unimodal processing. The present paper also proposes a framework for age-related AVI based on the current researches and provides a broad overview of alterations in AVI that occur with ageing.

Audiovisual Integration

Audition and vision are two important sensory systems that humans use to perceive the environment. The main region of the brain in which audition is perceived is the auditory cortex (AC), and the main area of the brain in which vision is perceived is the visual cortex (VC; Koelewijn et al., 2010; Fig. 1). Each sensory system comprises specialized pathways to translate external stimuli into neural signals that are interpreted by the brain. Although input signals from the same external environment during normal daily activities are transmitted through different modes into different cortical representations, these two sensory signals are automatically and effortlessly bound to provide a more accurate spatial message to shape and guide our behaviour. The process for binding auditory and visual signals is called AVI, which enables us to modify our own perception of the multisensory world and allows us to identify objects more effectively, even if the auditory stimuli or the visual stimuli are just under the threshold of perception. However, AVI is not merely the linear combination of two unisensory signals, as the result is sometimes much greater than the mere sum of the individual unisensory responses (Beauchamp, 2005). The classic behavioural phenomenon called the ‘redundant signal effect’ occurs when faster and more accurate responses occur to audiovisual signals than
to auditory-only or visual-only signals (Hershenson, 1962; Kinchla, 1974).

Additionally, because of the emergence of signals from different senses, AVI also leads to some illusions. Classic examples of sensory integration-induced illusions include the McGurk effect (McGurk & Macdonald, 1976), the ventriloquism effect (Bertelson & Radeau, 1981; Jack & Thurlow, 1973), the freezing effect (Vroomen & de Gelder, 2000), and the sound-induced flash illusion (Shams et al., 2000). Regarding the McGurk effect, watching the lip movements of the speaker alters an individual’s perception of audible content. A slight mismatch between auditory and visual information (for example, the auditory stimuli being Pa-Pa and the visual stimuli being Ka-Ka) may yield a different result (Ta-Ta; McGurk & Macdonald, 1976). Regarding the ventriloquism effect, the location of the sound is shifted to the visual event, as in the puppet illusion (Bertelson & Radeau, 1981; Jack & Thurlow, 1973). Although the ventriloquism effect has temporal and spatial restriction, the ventriloquism effect can occur even when the auditory and visual signals have no semantic value (Slutsky & Recanzone, 2001). For the freezing effect, the rapid visual display looks as if it is displayed much brighter than it is or is shown for a much longer time when accompanied by a rapidly synchronized sound (Vroomen & de Gelder, 2000). The sound-induced flash illusion is when one perceives two visual flashes when one visual flash is accompanied by two auditory beeps (Shams et al., 2000). Although audiovisual stimuli indeed induce illusions sometimes, AVI plays an important role in the correct perception of the external environment. Particularly for elderly adults, AVI was recognized as compensation for the decline of unisensory perception and signal processing (Diaconescu et al., 2013; Ren et al., 2018), and studies have suggested that elderly adults rely much more on AVI during speech perception (Maguiness et al., 2011). Furthermore, cognitive function in elderly adults can be improved through audiovisual training (Anguera et al., 2013; Kesler et al., 2013; Powers et al., 2009; Setti et al., 2014; Yang et al., 2018).

The superior colliculus (SC), mainly involved in orienting movements of the eyes (Stein & Meredith, 1993), receives converging auditory, visual and somatosensory afferents from primary cortical and subcortical sources, as has primarily been found in animal studies (Wallace et al., 1993). Presently, the SC is be regarded as classical AVI region. Besides, numerous association cortices are thought to play an important role in the integration of information from different modalities (Fig. 1). The superior temporal gyrus (STG) and superior temporal sulcus (STS), including auditory association areas, have been confirmed to be involved in AVI using an auditory/visual discrimination task (Stephen et al., 2010), an auditory/visual speech task (Baum & Beauchamp, 2014; Calvert et al., 2000; Stevenson et al., 2007; van Wassenhove et al., 2005), and real life objects recognition task (Beauchamp et al., 2004). In addition, related research has also indicated that neurons in the ventral lateral prefrontal cortex (VLPFC) of the frontal lobes of non-human primates, which are in charge of working memory, respond to audiovisual stimuli (Romanski, 2007). In addition, many regions that have long been considered to compose the unimodal cortex can also receive inputs from other sources, such as the AC (which also receives visual inputs; Beauchamp, 2005; van Wassenhove et al., 2005), the
VC (which also receives auditory inputs; Ren et al., 2018; Wright et al., 2003), the ventral intraparietal area (VIP, where neurons respond to visual and auditory events and is an area for three-dimensional integration; Slutsky & Recanzone, 2001), and the lateral intraparietal area (LIP, where neurons respond to visual and auditory events) of the VC (Linden et al., 1999).

**Behavioural Changes in AVI With Ageing**

Some previous studies using an auditory/visual detection task (Diederich et al., 2008; Mahoney et al., 2011; Peiffer et al., 2007), an auditory/visual discrimination task (Ren et al., 2016, 2018; Stephen et al., 2010; Wang et al., 2018; Wu et al., 2012; Yan et al., 2016; Zou et al., 2017), a sound-induced flash illusion task (DeLoss et al., 2013), a semantic audiovisual discrimination task (Diaconescu et al., 2013; Laurienti et al., 2006), or a speech perception task (Sekiyama et al., 2014; Tye-Murray et al., 2010) showed that elderly adults respond significantly slower to target than younger adults (Table 1). Based on unimodal reaction time data, AVI is extensively calculated through the race model, which is proposed by Miller (1982, 1986). The basic phenomenon is that detection responses are faster when signals are presented on bimodal audiovisual channels than on either auditory or visual channel alone, and this phenomenon is referred to as the “redundant signals effect.” The separate-activation model and co-activation model were raised to explain the redundant signals effect. The separate-activation model is that signals on different channels produce separate activations, and the activation from
| Publications           | Elderly adults | Younger adults | Task                                      |
|------------------------|----------------|----------------|-------------------------------------------|
|                        | Auditory       | Visual         | Audiovisual     | Auditory | Visual | Audiovisual |             |
| Peiffer et al. (2007)  | Equal          | Equal          | Lower          | Equal    | Equal  | Higher      |             |
| Diederich et al. (2008)| —              | 295            | 238            | —        | 171    | 149         |             |
| Mahoney et al. (2011) | 448            | 558            | 404            | 360      | 436    | 320         |             |
| Diaconescu et al. (2013)| 465 (119)    | 362 (74)       | 352 (100)      | 322 (82) | 286 (48)| 250 (48)    |             |
| Stephen et al. (2010) | 534            | 493            | 478            | 499      | 442    | 421         |             |
| Wu et al. (2012)      | 547            | 521            | 447            | 460      | 449    | 386         |             |
| Ren et al. (2016)     | 804 (121)      | 777 (164)      | 673 (110)      | 657 (110)| 581 (63)| 514 (61)    |             |
| Zou et al. (2017)     | Higher         | Higher         | Higher         | Lower    | Lower  | Lower       |             |
| Ren et al. (2018)     | 745 (27)       | 755 (25)       | 692 (25)       | 635 (27) | 658 (15)| 568 (16)    |             |
| Laurienti et al. (2006)| 714            | 614            | 527            | 623      | 538    | 485         |             |
| Diaconescu et al. (2013)| 1028 (128)  | 664 (75)       | 679 (55)       | 816 (141)| 622 (126)| 625 (124)   |             |
| Sekiyama et al. (2014)| Higher         | Higher         | Higher         | Lower    | Lower  | Lower       | Speech perception task |

Note. Elderly adults (age = 50–90), younger adults (age = 16–38). Left: The stimulus was presented to the left of the central fixation point; Right: The stimulus was presented to the right of the central fixation point. SDs are given in parentheses.
different channels is never combined in order to meet its criterion for responding. Because the response to a redundant signal is produced by the winner of the race, this model is commonly called “race model.” However, the co-activation model is that the activation from different channels is combined to provide activation to satisfy a single criterion, and the interaction between the auditory and visual signals was supposed to be occurred, which is called AVI. Quantitatively, the AVI was calculated by comparing the response to bimodal signals with race model.

Analysed using the race model, enhanced AVI was found in elderly adults, although they displayed significantly slower responses to both bimodal and unimodal stimuli than younger adults, as shown in Fig. 2A (Diederich et al., 2008; Laurienti et al., 2006). Laurienti et al. (2006) designed an auditory/visual discrimination task to detect response differences to audiovisual stimuli. In the experiment, the stimuli included the following three types: colourful visual discs (red, blue, or green), corresponding auditory words, and the combination of a visual circle and auditory words. During their experiment, the three types of stimuli were presented randomly, and participants were instructed to press a response button under their index finger to hear a blue word or to see a blue circle, and to press a button with their middle finger to hear a red word or to see a red circle. They found a larger performance gain in elderly adults (13.5%) than in younger adults (8.3%), showing that the response times to audiovisual stimuli exceeded the predictions of the race model (Laurienti et al., 2006). The successive study by Diederich et al. (2008) using a visual detection task obtained similar results (Diederich et al., 2008), which were also consistent with the results of Peiffer et al. (2007) who utilized an audiovisual detection task (Peiffer et al., 2007). Additionally, enhanced AVI for elderly adults compared with younger adults was also found in sound-induced flash illusion tasks (DeLoss et al., 2013) and speech perception tasks (Sekiyama et al., 2014).

However, some researchers found opposite results, reporting that elderly adults showed weaker AVI than younger adults (Fig. 2B). Tye-Murray tested and verified this view by an audiovisual speech discrimination task using a closed-set Build-A-Sentence (BAS) test and the City University of New York (CUNY) Sentence Test (Tye-Murray et al., 2010), and their results showed that younger adults show higher AVI than elderly adults during speech perception. A similar result was also obtained by Ganesh et al. (2017) using speech perception task by a specific paradigm, in which a short audiovisual context made of coherent or incoherent speech material was presented before an incongruent audiovisual target likely to provide fusion (Ganesh et al., 2017). Their results showed that elderly adults display more unbinding than younger participants, that is, a reduction in the amount of audiovisual interaction. In addition, research results using an auditory/visual detection task also found a weaker AVI effect in elderly adults (Mahoney et al., 2011), and the consistent result was also observed recently using auditory/visual discrimination task (Ren et al., 2016; Wu et al., 2012). Comparing with simple non-meaning signal, much more cognitive recourse and brain regions are needed to process complex semantic stimuli and dynamic speech stimuli (Stevenson & Wallace, 2013). Besides, the discrimination task need additional process of identification comparing with detection task, and the two tasks are mediated by distinct neural pathways (Gleiss &
Audiovisual integration effect

| Perspective | The AVI effect is higher in elderly adults | The AVI effect was weaker in elderly adults |
|-------------|------------------------------------------|------------------------------------------|
| Probability difference | ![Graph A](image1) | ![Graph B](image2) |
| Response Time (ms) | ![Graph A](image1) | ![Graph B](image2) |

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**Fig. 2.** Direct Comparison of AVI Effect Between Elderly and Younger Adults, and the Latest Researches Adopting Each Perspective

Note. The curves denote the cumulative probability difference, which illustrates substantial behavioural AVI in audiovisual condition compared to race model predictions. (A) Some investigations have showed higher AVI effect for elderly adults than younger adults. (B) However, some investigations showed weaker AVI effect for elderly adults than younger adults.

Kayser, 2013; Hillis & Brainard, 2007). For example, their demands on visual stimulus processing are quite different. Visual stimulus detection requires discriminating the luminance diversity of the image associated with the light reflected from adjacent objects, however, visual stimulus identification demands a fixed response to light reflected from an object independent of illumination. Moreover, most of the aforementioned studies evaluated AVI effect using race model, but the measurement using response facilitation between multimodal and unimodal was also applied (Tye-Murray et al., 2010), and due to the different evaluation index, it is difficult to compare the AVI effect. Therefore, Tye-Murray et al. (2010), Mahoney et al. (2011), and Ren et al. (2016) proposed that the different experimental materials, paradigms, and analysis methods might contribute to conflicting reports. Given that numerous factors influence AVI, the present data are insufficient to determine whether AVI effect is higher or weaker for elderly adults than younger adults. A systematic investigation of the alterations in AVI with ageing is needed in the future.

Additionally, with the exception of diversity for AVI quantity between elderly and younger adults, Laurienti et al. (2006) also reported that elderly adults have a much wider time window of AVI (330–690 ms and 730–740 ms) than younger adults (340–550 ms). Besides, the time for greatest response facilitation in audiovisual condition (peak benefit) was delayed at 520 ms in elderly adults than at 450 ms in younger adults (Fig. 3A) using an auditory/visual discrimination task (Laurienti et al., 2006). The wider time window for AVI was also found in elderly adults (188–380 ms) than younger adults (196–356 ms) by Peiffer et al. (2007) using an auditory/visual detection task; however, the peak benefit
Fig. 3. The Time Window of AVI for Elderly and Younger Adults

Note. (A) A wider time window for behavioural facilitation was elicited by central audiovisual stimuli in elderly adults (Laurienti et al., 2006), (B) however, wider and delayed time window for behavioural facilitation was elicited by peripheral audiovisual stimuli (Wu et al., 2012).

was elicited at approximately the same time point between elderly and younger adults (Peiffer et al., 2007). When the uninformed visual stimuli were presented at a peripheral angle of 12°, the wider time window for elderly adults (260–540 ms) relative to younger adults (240–450 ms) was also elicited (Wu et al., 2012), as shown in diagram Fig. 3B. And the wider time window for AVI was also occurred in Ren et al.’s (2016) study when the stimuli were presented peripherally (Ren et al., 2016). All these studies indicated that the speed of peripheral sensory processing slows in elderly adults and that the AVI effect cannot compensate for this decline in peripheral sensory processing (Diederich et al., 2008). This discrepancy may have resulted from an attention bias between the central vision field and the peripheral vision field. Based on the investigations above, we hypothesize that the time window for integration is obviously wider for elderly adults than for younger adults and that the time window for integration elicited by peripheral audiovisual stimuli is remarkably delayed relative to that elicited by central audiovisual stimuli (Fig. 3).

**Neural Diversity in AVI Between Younger and Elderly Adults**

fMRI, which uses metabolic signals to detect changes in blood flow and metabolism in the brain while a subject participates in cognitive tasks, is a technology with high spatial resolution. This method enables researchers to identify brain regions that are
activated during cognitive tasks and to test hypotheses about the anatomy in relation to brain function (Gazzaniga et al., 2008). Over the last few decades, studies have revealed a decrease in the magnitude of the blood oxygen level-dependent (BOLD) contrast response within the primary visual cortices, AC, and dorsolateral prefrontal cortex in elderly adults compared with younger adults during visual stimulus processing that does not require higher order processing (e.g., passively viewing a flashing checkerboard; Cliff et al., 2013; Huettel et al., 2001; Rypma & D’Esposito, 2000). These findings suggest that elderly adults show a reduced response in auditory sensory processing and visual sensory processing with increasing age. Baum and Beauchamp (2014) investigated the diversity of the haemodynamic responses between elderly and younger adults using an audiovisual speech perception task, and their results showed smaller response amplitudes and larger within-subject variability in elderly adults in the left STS, the left AC, and the left VC during response to audiovisual speech (Baum & Beauchamp, 2014). Considering that elderly adults exhibit decreased performance and increased trial-to-trial variability on a range of cognitive tasks, Baum and Beauchamp further proposed that increased neural variability may be related to the performance declines in audiovisual stimuli processing. Nevertheless, to our knowledge, no studies have directly compared the effect of ageing on AVI utilizing fMRI, but such investigations are necessary to confirm the compensation mechanism of the ageing brain. Diaconescu et al. (2013) used another important research tool, namely, structural MRI, to measure the brain activity on areas involved in AVI (Diaconescu et al., 2013). They designed a simple detection task and a semantic classification task to evaluate AVI effect using a 3.0 T Siemens Tim MAGNETOM Trio MRI scanner with a 12-channel head coil to acquire the scans. The data analysis showed that elderly adults had significantly reduced grey matter volume in the frontal, parietal, temporal and occipital lobes and significantly reduced white matter pathways in the
frontal lobe compared with younger adults (Fig. 4). However, their MEG results showed that elderly adults demonstrated increased activity in PP and MP regions compared to younger adults. Based on this research, it is reasonable to speculate that the magnitude of the BOLD contrast in AVI areas may also increase with age to compensate age-related functional decline, but this hypothesis needs to be verified in future research.

In contrast, event-related potentials (ERPs) are better suited to address questions regarding the time course of cognition than to elucidate the brain structures that produce electrical events (Gazzaniga et al., 2008). Early auditory ERP studies showed that the first and second positive peak (P1 and P2) and the first negative peak (N1) in ERPs increase with age (de Chicchis et al., 2002; Tremblay et al., 2003), while the second negative peak (N2) is diminished or disappears (Anderer et al., 1996; Bertoli & Probst, 2005; Čeponienė et al., 2008; de Chicchis et al., 2002). However, a few investigations have demonstrated that the P2 and N1 are diminished or unchanged with age, and they indicate that the P1 most likely results from alterations in prefrontal cortex–thalamic gating, while the N1 and P2 are linked to sensory-attentional interactions (Čeponienė et al., 2008). The limited number of studies investigating changes in visual processing with ageing have illustrated that visual evoke potential (VEP) amplitudes diminish with age and that their waveform morphology loses complexity (Bertoli & Probst, 2005; Čeponienė et al., 2008; Dustman et al., 1981; Tremblay et al., 2003). All these studies on age-related deficits during unsensory (auditory or visual) processing indicate ERP changes with age, and the findings of these studies can provide evidence for cognitive dysfunction diagnoses. However, typically, people use a combination of inputs to perceive the world, so in the last few decades, researchers have devoted more attention to investigating changes in AVI that occur with age. Setti et al. (2011) designed an audiovisual temporal order judgement task to investigate the correlation between cross-modal temporal discrimination deficits characterizing elderly adults and ERPs (Setti et al., 2011). They found that elderly adults had lower hit rates than younger adults (Stimulus Onset Asynchrony [SOA] = 270 ms); moreover, elderly adults had smaller P1 amplitudes for visual stimuli in audition-leading vision trials (V-leading-A condition, Fig. 5A) and smaller N1 amplitudes for auditory stimuli in audition-lagging vision trials (A-leading-V condition, Fig. 5B) in the SOA = 270 ms condition. These results indicate that deficits in cross-modal sensory processing arise with age at both the neural and behavioural levels. In another study by Setti et al. (2011) using the sound-induced flash illusion paradigm, a similar conclusion—that audiovisual processing was inefficient in the central nervous system—was acquired (Setti et al., 2011). However, studies using an auditory/visual discrimination task found that elderly adults exhibited higher levels of brain activity in early audiovisual processing (80–110 ms); this work further reported that for elderly adults, the earliest integration occurred in the occipital region (80–110 ms), and this effect was absent in younger adults (Ren et al., 2018). In addition, the superadditivity of visual and auditory information was also found by Zou et al. (2017) in the elderly group but not in the younger group using an auditory/visual discrimination task (Zou et al., 2017). Besides, many ERP studies have provided evidence demonstrating the capacity of the human brain to undergo learning-related structural plasticity, even in
elderly adults (Alain et al., 2014; Anguera et al., 2013; Yang et al., 2018; Zendel & Alain, 2014). Alain et al. (2014) reported that musical training improves auditory-processing abilities and that musicians experience less age-related decline in auditory-processing abilities than non-musicians (Alain et al., 2014; Zendel & Alain, 2014). After video game training designed based on the auditory/visual detection task, activity levels in brain regions involved in AVI, which was evaluated by EEG, were improved, achieving the same levels as those of younger adults, and this alteration remained for at least 6 months (Anguera et al., 2013). Additionally, recent studies found that even simple spatial or temporal discrimination training can improve executive ability and even lead to far-transfer effects in elderly adults (Setti et al., 2014; Yang et al., 2018).

Another important technique related to ERPs is MEG, which provides the same temporal resolution as ERPs but has an advantage stemming from the simultaneous localization of a signal source via magnetic fields to allow for a much better understanding of neural correlates (Gazzaniga et al., 2008). Stephen et al. (2010) used this technique to investigate active differences in an AVI area, namely, the STG, between elderly and younger adults during an audiovisual discrimination task (Stephen et al., 2010). The MEG results showed that the audiovisual response for Peak I (−60 ms) was higher in amplitude, and the audiovisual (AV) response for Peak II (−100 ms) was relatively lower in amplitude in elderly adults than younger adults (Fig. 6). Stephen et al. suggested that
elderly adults exhibited a poor AVI ability. However, the interpretation of the reduction in the amplitude elicited by audiovisual stimuli relative to the amplitude elicited by auditory-only stimuli is questionable. Using the same technique, Arnal et al. (2009) reported an amplitude reduction and latency shortening in the M100A peak in the audiovisual condition relative to that in the auditory-only condition, which indicated AVI in audiovisual condition (Arnal et al., 2009). A similar result—that amplitude reduction in the N1 and P2 components was elicited during audiovisual stimuli processing relative to auditory-only stimuli processing—was also reported in studies using ERPs in an auditory/visual detection task (Vroomen & Stekelenburg, 2010), an action perception task (Stekelenburg & Vroomen, 2007), and a speech perception task (Hisanaga et al., 2016; Pilling, 2009; Stekelenburg & Vroomen, 2007). The authors presumed that the accompanying visual information assists the participant in identifying the stimuli by reducing signal uncertainty and lowering computational demands for auditory brain areas, leading to a deactivation in audiovisual information processing. In Stephen et al.’s study, the amplitude of Peak II (~100 ms) for audiovisual stimuli was reduced in elderly adults relative to auditory-only stimuli, suggesting enhanced AVI (Fig. 6). In Stephen et al.’s study, the behavioural analysis based on race model revealed a weaker AVI effect in elderly adults than that in younger adults. These conflicting results further evidenced the need for neuroimaging studies to better understand information processing within the brain. The study of Ren et al. (2016) also found that AVI in elderly adults was weaker than that in younger adults (Ren et al., 2016), but their following ERP study using the same experimental paradigm found increased AVI in the early stage (80–110 ms) for elderly adults (Ren et al., 2018). Additionally, Laurienti et al. (2006), Peiffer et al. (2007), and Diederich et al. (2008) also reported enhanced AVI effect based on the analysis of race model behaviourally, but neuroimaging evidence is needed in future studies.

Both behavioural and neuroimaging data indicate that sensory processing declines with age, but given that healthy elderly adults can still identify audiovisual stimuli and can even perform similarly to younger adults, AVI may involve another compensatory mechanism that mitigates unisensory deficits (Laurienti et al., 2006). Although the primary brain regions for AVI are the same in elderly and younger adults, e.g., SC, STS,
STG, VIP, LIP and VLPF (Fig. 7), previous studies have shown that elderly adults can recruit additional brain areas to compensate for decreases in sensory processing. (Grady, 2009). Diaconescu et al. (2013) used MEG to record the responses of subjects (15 younger adults and 16 elderly adults) to semantically related cross-modal (V + A) and unimodal (V or A) stimuli to capture the different brain areas involved in AVI (Diaconescu et al., 2013). They found that elderly adults activated a distinct brain network when responding to cross-modal information composed of auditory and visual information. The particular regions that were activated was mainly located in the PP cortex and MP cortex (at 150–300 ms). A comparative study between elderly and younger adults conducted by Ren et al. (2018) using an auditory/visual discrimination task found activity in VC during audiovisual stimuli processing in elderly adults, but not in younger adults (Ren et al., 2018). Their results revealed that for elderly adults, the primary VC processing signal inputs from other sensory modalities, which indicating that elderly adults recruit primary VC involving in AVI. Based on the existing research, we
hypothesize that with ageing, signal transformation and processing change slightly, and as the specialization of different brain areas diminishes, a distinct brain network (including such regions as the PP and MP) participates in AVI to lessen the dysfunction in unimodal auditory and visual processing (Fig. 7).

**DISCUSSION**

It is commonly acknowledged that information processing declines with ageing (Abel et al., 2000; Grady, 2009; Kok, 2000; Gazzaniga et al., 2008; Setti et al., 2011). However, based on the available researches, we propose that a compensatory mechanism appears to mitigate dysfunction in sensory processing (Diaconescu et al., 2013; Freiherr et al., 2013; Ren et al., 2018), as elderly adults show much stronger enhancements in AVI than younger adults by recruiting other brain regions to respond to audiovisual stimuli (Diederich et al., 2008; Laurienti et al., 2006; Peiffer et al., 2007) and reducing hemispheric specialization (Goh, 2011; Grady, 2012; Lee et al., 2011; Ren et al., 2018). Some previous studies have indicated that elderly people rely more on audiovisual information than on unisensory information, and they can benefit more from the AVI of percept objects than younger adults (Maguiniss et al., 2011). Therefore, elderly adults retain distinct abilities for responding to sensory stimuli, and they can perform much better than or as well as younger adults in perceptual and cognitive tasks (Elliott et al., 2011).

However, all these cognitive impairments are irreversible, and the primary measure that we can take to postpone the decline is to develop technologies to assist clinical programmes in the early diagnosis of cognitive dysfunction. In addition, given the plasticity of the brain over one’s lifespan, the main objective of research on cognition is to develop cognitive training methods to maintain or strengthen individuals’ cognitive skills to ensure elderly adults’ independence and quality of life.

Based on the abovementioned researches, we have identified several research directions and challenges for future investigations. The combined application of distinct functional imaging methods, such as EEG, fMRI, MEG, and TMS, should be introduced to research on ageing. How does AVI change over one’s lifespan, and in which stages does such change occur should be investigated systematically? What alterations in AVI occur in patients with neurodegenerative disorders such as Alzheimer’s disease, Parkinson’s disease, and Huntington’s disease, and can some of these changes be used as structural neuroimaging biomarkers? Do alterations in AVI arising with age lead to other cognitive phenomena? Can we develop an effective cognitive training programme to improve brain function from auditory and visual perceptual perspective?

Given that auditory and visual perceptual training might be targeted in cognitive training methods to improve geriatric health, this review aimed to summarize current researches on AVI in the field of cognitive neuroscience and to identify possible directions for further research to help clinicians select the best therapy and treatment for age-related decline.
AUTHOR’S CONTRIBUTION

Y.R. and W.Y. constructed the outline of the paper, Z.X. and T.W. drew the figures, Y.R. wrote the manuscript and received suggestions from W.Y.

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

REFERENCES

Abel, S. M., Gigueré, C., Consoli, A., & Papsin, B. C. (2000). The effect of aging on horizontal plane sound localization. *Journal of the Acoustical Society of America*, 108(2), 743–752. https://doi.org/10.1121/1.429607

Alain, C., Zentel, B. R., Hutka, S., & Bidelman, G. M. (2014). Turning down the noise: The benefit of musical training on the aging auditory brain. *Hearing Research*, 308, 162–173. https://doi.org/10.1016/j.heares.2013.06.008

Anderer, P., Semlitsch, H. V., & Saletu, B. (1996). Multichannel auditory event-related brain potentials: Effects of normal aging on the scalp distribution of N1, P2, N2 and P300 latencies and amplitudes. *Electroencephalography and Clinical Neurophysiology*, 99(5), 458–472. https://doi.org/10.1016/s0013-4694(96)96518-9

Anguera, J. A., Boccanfuso, J., Rintoul, J. L., Al-Hashimi, O., Faraji, F., Janowich, J., Kong, E., Larraburo, Y., Rolle, C., Johnston, E., & Gazzaley, A. (2013). Video game training enhances cognitive control in older adults. *Nature*, 501(7465), 97–101. https://doi.org/10.1038/nature12486

Arnal, L. H., Morillon, B., Kell, C. A., & Giraud, A.-L. (2009). Dual neural routing of visual facilitation in speech processing. *Journal of Neuroscience*, 29(43), 13445–13453. https://doi.org/10.1523/JNEUROSCI.3194-09.2009

Babkoff, H., & Fostick, L. (2017). Age-related changes in auditory processing and speech perception: Cross-sectional and longitudinal analyses. *European Journal of Ageing*, 14(3), 269–281. https://doi.org/10.1007/s10433-017-0410-y

Baseler, H. A., Harris, R. J., Young, A. W., & Andrews, T. J. (2014). Neural responses to expression and gaze in the posterior superior temporal sulcus interact with facial identity. *Cerebral Cortex*, 24(3), 737–744. https://doi.org/10.1093/cercor/bhs360

Baum, S. H., & Beauchamp, M. S. (2014). Greater BOLD variability in older compared with younger adults during audiovisual speech perception. *PLOS ONE*, 9(10), Article e111121. https://doi.org/10.1371/journal.pone.0111121

Beauchamp, M. S. (2005). See me, hear me, touch me: Multisensory integration in lateral occipital-temporal cortex. *Current Opinion Neurobiology*, 15(2), 145–153. https://doi.org/10.1016/j.conb.2005.03.011

Beauchamp, M. S., Lee, K. E., Argall, B. D., & Martin, A. (2004). Integration of auditory and visual information about objects in superior temporal sulcus. *Neuron*, 41(5), 809–823. https://doi.org/10.1016/S0896-6273(04)00070-4

Bertelson, P., & Radeau, M. (1981). Cross-modal bias and perceptual fusion with auditory-visual spatial discordance. *Perception & Psychophysics*, 29(6), 578–584. https://doi.org/10.3758/bf03207374

Bertoli, S., & Probst, R. (2005). Lack of standard N2 in elderly participants indicates inhibitory processing deficit. *NeuroReport*, 16(17), 1933–1937. https://doi.org/10.1097/01.wnr.0000187630.45633.0a

Calvert, G. A., Campbell, R., & Brammer, M. J. (2000). Evidence from functional magnetic resonance imaging of crossmodal binding in the human heteromodal cortex. *Current Biology*, 10(11), 649–657. https://doi.org/10.1016/s0960-9822(00)00513-3
Čepionienė, R., Westerfield, M., Torki, M., & Townsend, J. (2008). Modality-specificity of sensory aging in vision and audition: Evidence from event-related potentials. *Brain Research, 1215*, 53–68. https://doi.org/10.1016/j.brainres.2008.02.010

Cliff, M., Joyce, D. W., Lamar, M., Dannhauser, T., Tracy, D. K., & Shergill, S. S. (2013). Aging effects on functional auditory and visual processing using fMRI with variable sensory loading. *Cortex, 49*(5), 1304–1313. https://doi.org/10.1016/j.cortex.2012.04.003

Craig, J. C., Rhodes, R. P., Busey, T. A., Kewley-Port, D., & Humes, L. E. (2010). Aging and tactile temporal order. *Attention, Perception, & Psychophysics, 72*(1), 226–235. https://doi.org/10.3758/APP.72.1.226

Cui, Q. N., O’Neill, W. E., & Paige, G. D. (2010). Advancing age alters the influence of eye position on sound localization. *Experimental Brain Research, 206*(4), 371–379. https://doi.org/10.1007/s00221-010-2413-1

de Chiconis, A. R., Carpenter, M., Cranford, J. L., & Hymel, M. R. (2002). Electrophysiologic correlates of attention versus distraction in young and elderly listeners. *Journal of the American Academy of Audiology, 13*(7), 383–391.

DeLoss, D. J., Pierce, R. S., & Andersen, G. J. (2013). Multisensory integration, aging, and the sound-induced flash illusion. *Psychology and Aging, 28*(3), 802–812. https://doi.org/10.1037/a0033289

Dey, A., & Sommers, M. S. (2015). Age-related differences in inhibitory control predict audiovisual speech perception. *Psychology and Aging, 30*(3), 634–646. https://doi.org/10.1037/pag0000033

Diaconescu, A. O., Hasher, L., & Mcintosh, A. R. (2013). Visual dominance and multisensory integration changes with age. *NeuroImage, 65*, 152–166. https://doi.org/10.1016/j.neuroimage.2012.09.057

Diederich, A., Colonius, H., & Schomburg, A. (2008). Assessing age-related multisensory enhancement with the time-window-of-integration model. *Neuropsychologia, 46*(10), 2556–2562. https://doi.org/10.1016/j.neuropsychologia.2008.03.026

Dustman, R. E., Snyder, E. W., & Schlehuber, C. J. (1981). Life-span alterations in visually evoked potentials and inhibitory function. *Neurobiology of Aging, 2*(3), 187–192. https://doi.org/10.1016/0197-4580(81)90019-1

Elliott, M. T., Wing, A. M., & Welchman, A. E. (2011). The effect of ageing on multisensory integration for the control of movement timing. *Experimental Brain Research, 213*(2–3), Article 291. https://doi.org/10.1007/s00221-011-2740-x

Fiacconi, C. M., Harvey, E. C., Sekuler, A. B., & Bennett, P. J. (2013). The influence of aging on audiovisual temporal order judgments. *Experimental Aging Research, 39*(2), 179–193. https://doi.org/10.1080/0361073X.2013.761896

Freiher, J., Lundström, J., Habel, U., & Reetz, K. (2013). Multisensory integration mechanisms during aging. *Frontiers in Human Neuroscience, 7*, Article 863. https://doi.org/10.3389/fnhum.2013.00863

Ganesh, A. C., Berthommier, F., & Schwartz, J.-L. (2017). Audiovisual binding for speech perception in noise and in aging. *Language Learning, 68*(S1), 193–220. https://doi.org/10.1111/lang.12271

Gazzaniga, M. S., Ivry, R. B., & Mangun, G. R. (2008). *Cognitive neuroscience: The biology of the mind* (3rd ed.). W. W. Norton & Company.

Gleiss, S., & Kayser, C. (2013). Eccentricity dependent auditory enhancement of visual stimulus detection but not discrimination. *Frontiers in Integrative Neuroscience, 7*, Article 52. https://doi.org/10.3389/fnint.2013.00052

Goh, J. O. S. (2011). Functional dedifferentiation and altered connectivity in older adults: Neural accounts of cognitive aging. *Aging and Disease, 2*(1), 30–48. http://www.aginganddisease.org/EN/Y2011/V2/I1/30

Grady, C. L. (2009). Functional neuroimaging studies of aging. *Encyclopedia of Neuroscience*, 417–424. https://doi.org/10.1016/B978-008045046-9.00103-0

Grady, C. L. (2012). The cognitive neuroscience of ageing. *Nature Reviews Neuroscience, 13*(7), 491–505. https://doi.org/10.1038/nrn3256

Gregoryjohnson, L. (2014). *The relationship between cognitive status and speech perception in normally aging adults* [Master thesis, University of South Alabama].

Gutcheon, A. (2014). Plasticity of the aging brain: New directions in cognitive neuroscience. *Science, 346*(6209), 579–582. https://doi.org/10.1126/science.1254604

Hershenson, M. (1962). Reaction time as a measure of intersensory facilitation. *Journal of Experimental...


*Psychology, 63*(3), 289–293. https://doi.org/10.1037/h0039516

Hillis, J. M., & Brainard, D. H. (2007). Distinct mechanisms mediate visual detection and identification. *Current Biology, 17*(19), 1714–1719. https://doi.org/10.1016/j.cub.2007.09.012

Hisanaga, S., Sekiyama, K., Igasaki, T., & Murayama, N. (2016). Language/culture modulates brain and gaze processes in audiovisual speech perception. *Scientific Reports, 6*, Article 35265. https://doi.org/10.1038/srep35265

Huettel, S. A., Singerman, J. D., & McCarthy, G. (2001). The effects of aging upon the hemodynamic response measured by functional MRI. *NeuroImage, 13*(1), 161–175. https://doi.org/10.1006/nimg.2000.0675

Jack, C. E., & Thurlow, W. R. (1973). Effects of degree of visual association and angle of displacement on the “ventriloquism” effect. *Perceptual & Motor Skills, 37*(3), 967–979. https://doi.org/10.1177/00315257303700360

Kesler, S., Hadi Hosseini, S. M., Heckler, C., Janelsins, M., Palesh, O., Mustian, K., & Morrow, G. (2013). Cognitive training for improving executive function in chemotherapy-treated breast cancer survivors. *Clinical Breast Cancer, 13*(4), 299–306. https://doi.org/10.1016/j.clbc.2013.02.004

Kincl, R. A. (1974). Detecting target elements in multielement arrays: A confusability model. *Perception & Psychophysics, 15*(1), 149–158. https://doi.org/10.3758/BF03205843

Koelewijn, T., Bronkhorst, A., & Theeuwes, J. (2010). Attention and the multiple stages of multisensory integration: A review of audiovisual studies. *Acta Psychologica, 134*(3), 372–384. https://doi.org/10.1016/j.actpsy.2010.03.010

Kok, A. (2000). Age-related changes in involuntary and voluntary attention as reflected in components of the event-related potential (ERP). *Biological Psychology, 54*(1–3), 107–143. https://doi.org/10.1016/S0301-0511(00)00054-5

Laurienti, P. J., Burdette, J. H., Maldjian, J. A., & Wallace, M. T. (2006). Enhanced multisensory integration in older adults. *Neurobiology of Aging, 27*(8), 1155–1163. https://doi.org/10.1016/j.neurobiolaging.2005.05.024

Lee, L.-P., Har, A. W.-Y., Ngai, C.-H., Lai, D. W. L., Lam, B. Y.-H., & Chan, C. C.-H. (2020). Audiovisual integrative training for augmenting cognitive-motor functions in older adults with mild cognitive impairment. *BMC Geriatrics, 20*, Article 64. https://doi.org/10.1186/s12877-020-1465-8

Lee, Y., Grady, C. L., Habak, C., Wilson, H. R., & Moscovitch, M. (2011). Face processing changes in normal aging revealed by fMRI adaptation. *Journal of Cognitive Neuroscience, 23*(11), 3433–3447. https://doi.org/10.1162/jocn_a_00026

Linden, J. F., Grunewald, A., & Anderssen, R. A. (1999). Responses to auditory stimuli in macaque lateral intraparietal area II. Behavioral modulation. *Journal of Neurophysiology, 82*(1), 343–358. https://doi.org/10.1152/jn.1999.82.1.343

Maguire, C., Setti, A., Burke, K. E., Kenny, R. A., & Newell, F. N. (2011). The effect of combined sensory and semantic components on audio–visual speech perception in older adults. *Frontiers in Aging Neuroscience, 3*, Article 19. https://doi.org/10.3389/fnagi.2011.00019

Mahoney, J. R., Li, P. C. C., Oh-Park, M., Verghese, J., & Holtzer, R. (2011). Multisensory integration across the senses in young and old adults. *Brain Research, 1426*, 43–53. https://doi.org/10.1016/j.brainres.2011.09.017

McGurk, H., & Macdonald, J. (1976). Hearing lips and seeing voices. *Nature, 264*(5588), 746–748. https://doi.org/10.1038/264746a0

Miller, J. (1982). Divided attention: Evidence for coactivation with redundant signals. *Cognitive Psychology, 14*(2), 247–279. https://doi.org/10.1016/0010-0285(82)90010-X

Miller, J. (1986). Timecourse of coactivation in bimodal divided attention. *Perception & Psychophysics, 40*(5), 331–343. https://doi.org/10.3758/BF03203025

Mozolic, J. L., Long, A. B., Morgan, A. R., Rawley-Payne, M., & Laurienti, P. J. (2011). A cognitive training intervention improves modality-specific attention in a randomized controlled trial of healthy older adults. *Neurobiology of Aging, 32*(4), 655–668. https://doi.org/10.1016/j.neurobiolaging.2009.04.013

Newell, F. N. (2012). Inefficient cross-sensory temporal integration in older persons with a history of falling. *Seeing and Perceiving, 25*, 210. https://doi.org/10.1163/187847612X648387

Peiffer, A. M., Mozolic, J. L., Hugenschmidt, C. E., & Laurienti, P. J. (2007). Age-related multisensory
enhancement in a simple audiovisual detection task. *NeuroReport*, 18(10), 1077–1081. https://doi.org/10.1097/WNR.0b013e3281e72ae7

Pilling, M. (2009). Auditory event-related potentials (ERPs) in audiovisual speech perception. *Journal of Speech, Language, and Hearing Research*, 52(4), 1073–1081. https://doi.org/10.1044/1092-4388(2009-07276)

Pilz, K. S., Konar, Y., Vuong, Q. C., Bennett, P. J., & Sekuler, A. B. (2011). Age-related changes in matching novel objects across viewpoints. *Vision Research*, 51(17), 1958–1965. https://doi.org/10.1016/j.visres.2011.07.009

Poliafko, E., Ashworth, S., Lowe, C., & Spence, C. (2006). Vision and touch in ageing: Crossmodal selective attention and visuotactile spatial interactions. *Neuropsychologia*, 44(4), 507–517. https://doi.org/10.1016/j.neuropsychologia.2005.07.004

Powers, A. R., Hillock, A. R., & Wallace, M. T. (2009). Perceptual training narrows the temporal window of multisensory binding. *Journal of Neuroscience*, 29(39), 12265–12274. https://doi.org/10.1523/JNEUROSCI.3501-09.2009

Ren, Y., Ren, Y., Yang, W., Tang, X., Wu, F., Wu, Q., Takahashi, S., Ejima, Y., & Wu, J. (2018). Comparison for younger and older adults: Stimulus temporal asynchrony modulates audiovisual integration. *International Journal of Psychophysiology*, 124, 1–11. https://doi.org/10.1016/j.ijpsycho.2017.12.004

Ren, Y., Yang, W., Nakahashi, K., Takahashi, S., & Wu, J. (2016). Audiovisual integration delayed by stimulus onset asynchrony between auditory and visual stimuli in older adults. *Perception*, 46(2), 205–218. https://doi.org/10.1177/0301006616673850

Romanski, L. M. (2007). Representation and integration of auditory and visual stimuli in the primate ventral lateral prefrontal cortex. *Cerebral Cortex, 17*(S1), i61–i69. https://doi.org/10.1093/cercor/bhm099

Rypma, B., & D’Esposito, M. (2000). Isolating the neural mechanisms of age-related changes in human working memory. *Nature Neuroscience*, 3(5), 509–515. https://doi.org/10.1038/74889

Sekiya, K., Soshi, T., & Sakamoto, S. (2014). Enhanced audiovisual integration with aging in speech perception: A heightened McGurk effect in older adults. *Frontiers in Psychology*, 5, Article 323. https://doi.org/10.3389/fpsyg.2014.00323

Setti, A., Burke, K. E., Kenny, R. A., & Newell, F. N. (2011). Is inefficient multisensory processing associated with falls in older people? *Experimental Brain Research*, 209(3), 375–384. https://doi.org/10.1007/s00221-011-2560-z

Setti, A., Stapleton, J., Leahy, D., Walsh, C., Kenny, R. A., & Newell, F. N. (2014). Improving the efficiency of multisensory integration in older adults: Audiovisual temporal discrimination training reduces susceptibility to the sound-induced flash illusion. *Neuropsychologia*, 61, 259–268. https://doi.org/10.1016/j.neuropsychologia.2014.06.027

Shams, L., Kamitani, Y., & Shimojo, S. (2000). What you see is what you hear. *Nature*, 408(6814), 788. https://doi.org/10.1038/35048669

Slutsky, D. A., & Recanzone, G. H. (2001). Temporal and spatial dependency of the ventriloquism effect. *NeuroReport*, 12(1), 7–10. https://journals.lww.com/neuroreport/Fulltext/2001/01220/Temporal_and spatial_dependency_of_the.9.aspx

Stapleton, J., Setti, A., Doheny, E. P., Kenny, R. A., & Newell, F. N. (2014). A standing posture is associated with increased susceptibility to the sound-induced flash illusion in fall-prone older adults. *Experimental Brain Research*, 232(2), 423–434. https://doi.org/10.1007/s00221-013-3750-7

Stein, B. E., & Meredith, M. A. (1993). *The merging of the senses*. MIT Press.

Stekelenburg, J. J., & Vroomen, J. (2007). Neural correlates of multisensory integration of ecologically valid audiovisual events. *Journal of Cognitive Neuroscience*, 19(12), 1964–1973. https://doi.org/10.1162/jocn.2007.19.12.1964

Stephen, J. M., Knoefel, J. E., Adair, J., Hart, B., & Aine, C. J. (2010). Aging-related changes in auditory and visual integration measured with MEG. *Neuroscience Letters*, 484(1), 76–80. https://doi.org/10.1016/j.neulet.2010.08.023

Stevenson, R. A., Geoghegan, M. L., & James, T. W. (2007). Superadditive BOLD activation in superior temporal sulcus with threshold non-speech objects. *Experimental Brain Research*, 179(1), 85–95. https://doi.org/10.1007/s00221-006-0770-6

Stevenson, R. A., & Wallace, M. T. (2013). Multisensory temporal integration: Task and stimulus
dependencies. *Experimental Brain Research*, 227(2), 249–261. https://doi.org/10.1007/s00221-013-3507-3

toril, P., Reale, J. M., Mayas, J., & Ballestros, S. (2016). Video game training enhances visuospatial working memory and episodic memory in older adults. *Frontiers in Human Neuroscience*, 10, Article 206. https://doi.org/10.3389/fnhum.2016.00206

tremblay, K. L., Piskosz, M., & Souza, P. (2003). Effects of age and age-related hearing loss on the neural representation of speech cues. *Clinical Neurophysiology*, 114(7), 1332–1343. https://doi.org/10.1016/s1388-2450(03)00114-7

tyemurray, N., sommers, M., spehar, B., myerson, J., & Hale, S. (2010). Aging, audiovisual integration, and the principle of inverse effectiveness. *Ear and Hearing*, 31(5), 636–644. https://doi.org/10.1097/AUD.0b013e3181dd7ff

tvan Wassenhove, V., Grant, K. W., & Poeppel, D. (2005). Visual speech speeds up the neural processing of auditory speech. *Proceedings of National Academy of Sciences of the United States of America*, 102(4), 1181–1186. https://doi.org/10.1073/pnas.0408949102

vroomen, J., & de Gelder, B. (2000). Sound enhances visual perception: Cross-modal effects of auditory organization on vision. *Journal of Experimental Psychology: Human Perception and Performance*, 26(5), 1583–1590. https://doi.org/10.1037/0096-1523.26.5.1583

vroomen, J., & Stekelenburg, J. J. (2010). Visual anticipatory information modulates multisensory interactions of artificial audiovisual stimuli. *Journal of Cognitive Neuroscience*, 22(7), 1583–1596. https://doi.org/10.1162/jocn.2009.21308

wallace, M. T., Meredith, M. A., & Stein, B. E. (1993). Converging influences from visual, auditory, and somatosensory cortices onto output neurons of the superior colliculus. *Journal of Neurophysiology*, 69(6), 1797–1809. https://doi.org/10.1152/jn.1993.69.6.1797

wang, B., Li, P., Li, D., niu, Y., yan, T., Li, T., cao, R., yan, P., guo, Y., yang, W., ren, Y., li, x., wang, F., yan, T., wu, J., zhang, H., & xiang, J. (2018). Increased functional brain network efficiency during audiovisual temporal asynchrony integration task in aging. *Frontiers in Aging Neuroscience*, 10, Article 316. https://doi.org/10.3389/fnagi.2018.00316

wright, T. M., Pelphey, K. A., Allison, T., Mckeown, M. J., & McCarthy, G. (2003). Polysensory interactions along lateral temporal regions evoked by audiovisual speech. *Cerebral Cortex*, 13(10), 1034–1043. https://doi.org/10.1093/cercor/13.10.1034

wu, J. L., Yang, W. P., gao, Y. L., & kimura, T. (2012). Age-related multisensory integration elicited by peripherally presented audiovisual stimuli. *NeuroReport*, 23(10), 616–620. https://doi.org/10.1097/WNR.0b013e3283552b0f

yan, T., bi, X., zhang, M., wang, W., yao, Z., yang, W., & wu, J. (2016). Age-related oscillatory theta modulation of multisensory integration in frontocentral regions. *NeuroReport*, 27(11), 796–801. https://doi.org/10.1097/WNR.0000000000000609

yang, W., guo, A., li, Y., qiu, J., li, S., yin, S., chen, J., & ren, Y. (2018). Audio-visual spatiotemporal perceptual training enhances the P300 component in healthy older adults. *Frontiers in Psychology*, 9, Article 2537. https://doi.org/10.3389/fpsyg.2018.02537

zende, B. R., & Alain, C. (2014). Enhanced attention-dependent activity in the auditory cortex of older musicians. *Neurobiology of Aging*, 35(1), 55–63. https://doi.org/10.1016/j.neurobiology.2013.06.022

zou, Z., Chau, B. K. H., ting, K.-H., & chan, C. C. H. (2017). Aging effect on audiovisual integrative processing in spatial discrimination task. *Frontiers in Aging Neuroscience*, 9, Article 374. https://doi.org/10.3389/fnagi.2017.00374

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