Age-equivalent Top–Down Modulation during Cross-modal Selective Attention

Maria J. S. Guerreiro[1,2*], Joaquin A. Anguera[1], Jyoti Mishra[1], Pascal W. M. Van Gerven[2], and Adam Gazzaley[1]

Abstract

■ Selective attention involves top–down modulation of sensory cortical areas, such that responses to relevant information are enhanced whereas responses to irrelevant information are suppressed. Suppression of irrelevant information, unlike enhancement of relevant information, has been shown to be deficient in aging. Although these attentional mechanisms have been well characterized within the visual modality, little is known about these mechanisms when attention is selectively allocated across sensory modalities. The present EEG study addressed this issue by testing younger and older participants in three different tasks: Participants attended to the visual modality and ignored the auditory modality, attended to the auditory modality and ignored the visual modality, or passively perceived information presented through either modality. We found overall modulation of visual and auditory processing during cross-modal selective attention in both age groups. Top–down modulation of visual processing was observed as a trend toward enhancement of visual information in the setting of auditory distraction, but no significant suppression of visual distraction when auditory information was relevant. Top–down modulation of auditory processing, on the other hand, was observed as suppression of auditory distraction when visual stimuli were relevant, but no significant enhancement of auditory information in the setting of visual distraction. In addition, greater visual enhancement was associated with better recognition of relevant visual information, and greater auditory distractor suppression was associated with a better ability to ignore auditory distraction. There were no age differences in these effects, suggesting that when relevant and irrelevant information are presented through different sensory modalities, selective attention remains intact in older age. ■

INTRODUCTION

Selective attention requires attending to relevant information and ignoring irrelevant information, thereby managing the allocation of one's limited processing capacity to information that is most relevant for ongoing goals and behavior (Chun, Golomb, & Turk-Browne, 2011). This cognitive construct is driven by prefrontal brain regions in a top–down fashion to enhance cortical responses for relevant information and suppress cortical responses for irrelevant information (Gazzaley, Cooney, McEvoy, Knight, & D'Esposito, 2005).

In recent years, top–down modulation has been well characterized for visual selective attention during both object-based and feature-based attention (Zanto & Gazzaley, 2009; Gazzaley, Cooney, McEvoy, et al., 2005; Hopf, Schoenfeld, & Heinze, 2005; Downing, Liu, & Kanwisher, 2001). In contrast, considerably less is known about top–down modulation in cross-modal selective attention (Mishra & Gazzaley, 2012; Talsma, Senkowski, Soto-Faraco, & Woldorff, 2010), when relevant information and irrelevant information are presented in different sensory modalities. Some studies suggest that top–down modulation across modalities might be implemented similarly to top–down modulation within modalities (e.g., Johnson & Zatorre, 2005, 2006), when relevant information and irrelevant information are presented in the same sensory modality. For example, Johnson and Zatorre (2005, 2006) demonstrated that attending to visual shapes and ignoring concurrently presented auditory melodies leads to increased activity in visual areas and decreased activity in auditory areas relative to passively viewing and hearing (and vice versa). Other studies have only evidenced attentional modulation of the sensory cortices responsible for processing the goal-relevant information (e.g., Weissman, Warner, & Woldorff, 2004; Rees, Frith, & Lavie, 2001). In one such study (Weissman et al., 2004), participants were presented with concurrent visual and auditory letters, which could be congruent or incongruent, and were asked to focus their attention on one of the two sensory modalities at a time. In this study, activity in sensory areas responsible for processing the relevant modality increased as the irrelevant letter became more distracting. Furthermore, the larger the increase of activity in the sensory cortex processing the relevant letter, the less behavioral interference there was from the irrelevant letter. These findings suggest that enhancement of the sensory

[1]University of California, San Francisco, [2]Maastricht University
*Maria J. S. Guerreiro is now at Biological Psychology and Neuropsychology, University of Hamburg, Hamburg, Germany.

Journal of Cognitive Neuroscience 26:12, pp. 2827–2839
doi:10.1162/jocn_a_00685

cortices processing the relevant modality may be sufficient to offset distraction by irrelevant information in a cross-modal situation.

Within the field of cognitive aging, deficits in top–down modulation have been proposed to account for the pattern of attention and memory decline typically observed in older adults (Gazzaley, 2013; Gazzaley & D'Esposito, 2007). This age-related top–down modulation deficit has been consistently demonstrated in visual selective attention, where it has been shown to be specific to suppression of irrelevant visual information, whereas enhancement of relevant visual information is unaffected by aging (Gazzaley, Cooney, Rissman, & D'Esposito, 2005). In addition, this age-related suppression deficit has been shown to be restricted to the early stages of visual cortical processing (Gazzaley et al., 2008).

We have recently proposed that age-related distractibility is modality dependent (Guerreiro, Murphy, & Van Gerven, 2010). Specifically, this hypothesis predicts that age-related distraction is more likely to be present (1) in unimodal than in cross-modal selective attention conditions and (2) whenever distraction is visual, regardless of the sensory modality in which relevant information is presented. Empirical studies aimed at investigating the role of sensory modality in selective attention have provided mixed evidence for age-related differences in cross-modal selective attention. In fact, some studies corroborate the notion that cross-modal selective attention remains intact in aging (e.g., Guerreiro, Adam, & Van Gerven, 2012, 2014; Mishra & Gazzaley, 2013; Hugenschmidt, Peiffer, McCoy, Hayasaka, & Laurienti, 2009). In contrast, other studies indicate an asymmetry in cross-modal distraction with age, whereby older adults are more affected than younger adults by visual distraction when attending to the auditory modality, but equally affected by auditory distraction when attending to the visual modality (Guerreiro, Murphy, & Van Gerven, 2013; Guerreiro & Van Gerven, 2011).

The goal of this study was twofold. First, we sought to further investigate top–down modulation during cross-modal selective attention. The literature reviewed above makes conflicting predictions about top–down modulation in cross-modal selective attention. On the one hand, top–down modulation might operate cross-modally in a manner analogous to that observed in visual selective attention (i.e., enhancement of sensory processing in the attended modality and suppression of sensory processing in the unattended modality; Johnson & Zatorre, 2005, 2006). Alternatively, top–down modulation might operate to a lesser degree in cross-modal conditions (e.g., only enhancement of sensory processing of relevant information; Weissman et al., 2004). To address this question, we used a variant of the unimodal paradigm typically employed to investigate top–down modulation (e.g., Zanto & Gazzaley, 2009; Gazzaley, Cooney, McEvoy, et al., 2005) in combination with EEG. Although the studies reviewed above presented targets and distractors concurrently (e.g., Johnson & Zatorre, 2005, 2006; Weissman et al., 2004), previous studies have shown that modulation of neural activity also occurs based on differential attention to sequentially presented stimuli as employed here (e.g., Gazzaley, Cooney, McEvoy, et al., 2005). The second goal was to investigate age-related differences in top–down modulation during cross-modal selective attention to sequential stimuli. On the basis of the hypothesis that age-related distraction is modality dependent (Guerreiro et al., 2010, 2013; Guerreiro & Van Gerven, 2011), we predicted that older adults would show a deficit relative to younger adults in the ability to suppress irrelevant visual information during auditory attention, but age-equivalent suppression of irrelevant auditory information during visual attention. If, however, older adults have intact cross-modal selective attention abilities (Mishra & Gazzaley, 2013; Hugenschmidt et al., 2009), we expected to find age-equivalent top–down modulation of both visual and auditory processing in the present cross-modal paradigm.

METHODS

Participants

Twenty younger (aged 19–29 years, M = 24.1 years, SD = 3.0, 10 men) and 20 older adults (aged 62–80 years, M = 68.7 years, SD = 5.1, 10 men) took part in this experiment. All participants gave informed consent to participate in this study according to the procedures approved by the Committee for Human Research at the University of California. Participants were screened to ensure that they were healthy; had no history of neurological, psychiatric, or vascular conditions that could interfere with the behavioral or neural measures; were not depressed; and were not taking any psychotropic or hypertensive medications. All participants reported having normal (or corrected-to-normal) vision and no hearing deficits and were right-handed. In addition, only participants who had no knowledge of Portuguese participated in this experiment. This was done to ensure that participants did not semantically process the auditory stimuli used in this study, which consisted of Portuguese words, but instead relied on their phonological characteristics for task performance.

Neuropsychological Testing

Before experimental testing, the older participants were administered a battery of neuropsychological tests that assessed verbal learning (California Verbal Learning Test-II; Delis, Kramer, Kaplan, & Ober, 2000), visual-spatial function (copy of a modified Rey–Osterrieth figure), visual-episodic memory (memory for details of a modified Rey–Osterrieth figure), visual-motor sequencing (Trail Making Test A and B; Tombaugh, 2004), phonemic fluency (words beginning with the letter "D"), semantic fluency (animals), calculation ability (mental arithmetic subtest, WAIS-R; Wechsler, 1981), executive functioning (Stroop Color–Word Test; Stroop, 1935), working memory (digit span subtest, WAIS-R; Wechsler, 1981), and speed of processing (digit symbol subtest, WAIS-R; Wechsler, 1981). All older adults were found to be cognitively intact (i.e., within two standard deviations; Anguera & Gazzaley, 2012; Clapp & Gazzaley, 2012; Zanto, Hennigan, Östberg, Clapp, & Gazzaley, 2010) relative to normative values for age-matched controls.

Selective Attention Tasks

Throughout the three conditions of the experimental paradigm (Figure 1), participants viewed two faces and heard two voice stimuli presented sequentially and in a random order. Each stimulus was presented for 800 msec and was followed by a 200-msec ISI. After four stimuli, there was a 4-sec delay period in which the relevant stimuli—if any—were to be remembered. After the delay, the probe stimulus was presented, to which a response had to be provided within a 2-sec period. Following this period, there was a 4-sec intertrial interval.

The experiment consisted of three tasks that differed in the instructions given at the beginning of each run. (1) In the remember faces task, participants were instructed to remember the face stimuli and to ignore the voice stimuli. (2) In the remember voices task, participants were instructed to remember the voice stimuli and to ignore the face stimuli. The probe stimulus was a face in the remember faces task and a voice in the remember voices task. Once the probe stimulus was presented, participants had to indicate with a button press whether it matched one of the relevant cue stimuli presented within the trial. (3) In the passive task, participants were instructed to passively view the faces and hear the voices without attempting to analyze or memorize them. Instead of a probe stimulus, an arrow was presented, and participants had to indicate its direction with a button press. This passive task has been used as the control condition in several previous experiments (e.g., Chadick & Gazzaley, 2011; Gazzaley et al., 2008; Gazzaley, Cooney, McEvoy, et al., 2005; Gazzaley, Cooney, Rissman, et al., 2005).

Each task was presented in three separate runs, each of which contained 20 trials. The order of the tasks was counterbalanced across participants provided that the passive task was performed first (to avoid carryover effects of attending to one stimulus type from working memory to passive conditions), such that half of the participants performed the remember faces task before the remember voices task and the other half received opposite instructions. Before the tasks, participants performed a practice run that contained four trials of each condition. During this practice run, the intensity of the auditory stimuli was individually adjusted in the range of 60–65 dB, so they were heard at a comfortable level for each participant. None of the stimuli presented during the practice run were presented during the experiment proper.

Participants were asked to respond to the probe and arrow stimuli as quickly and accurately as possible. The function of the response buttons was counterbalanced across participants, such that half of the participants pressed the right button for a “match” response and the left button for a “nonmatch” response whereas the other half received opposite instructions. Each stimulus was presented twice

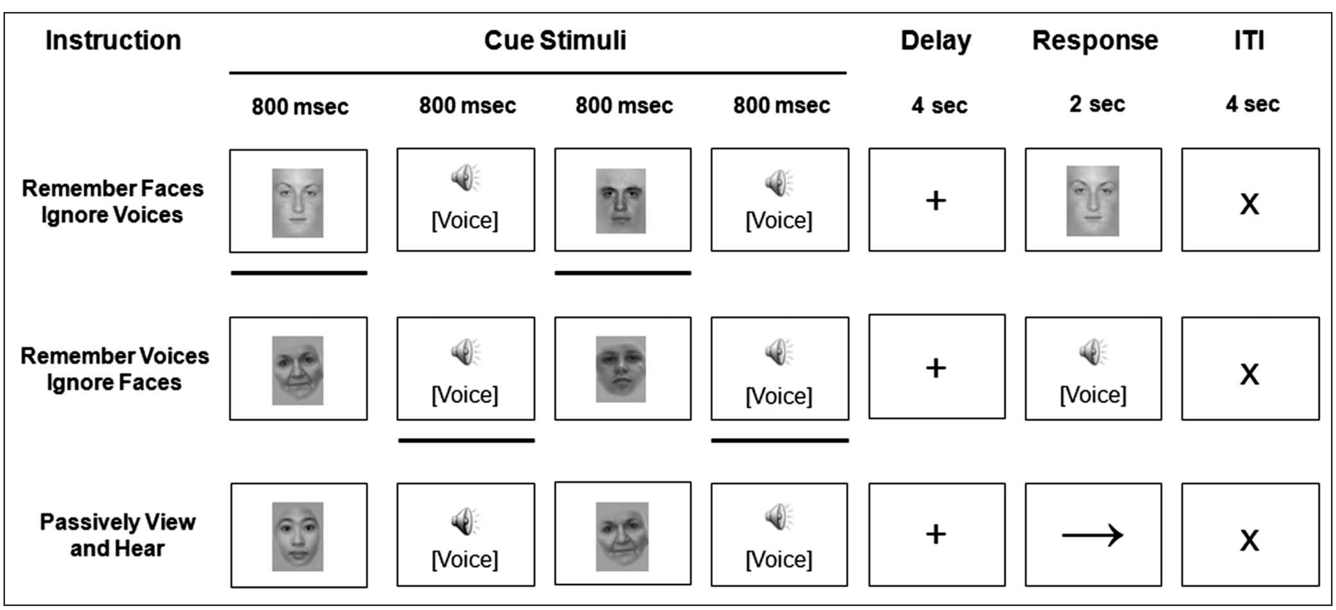

Figure 1. Experimental paradigm. Participants were required to indicate with a button press whether the probe stimulus matched one of the previously presented stimuli (i.e., a face or a voice). In the passive task, an arrow was presented and participants were required to indicate with a button press the direction of the arrow. The lines below the stimuli highlight task relevance in this illustration.

in each condition (or yet a third time if it was also presented as the probe stimulus).

Postexperiment Recognition Tasks

After completion of the EEG experiment, unexpected memory tasks were administered to assess recognition of stimuli presented during the EEG session. Each participant viewed 90 faces and heard 90 voice stimuli, half of which had been presented during the EEG session. All previously presented stimuli used in the postexperiment recognition task had been presented an equal number of times during the course of the experiment (those that were presented an unequal number of times because they were presented as both cue and probe stimuli were omitted) and represented a balanced combination of stimuli taken from each condition.

The order of the postexperiment recognition tasks was counterbalanced across participants, such that participants who performed the remember faces task before the remember voices task performed the face recognition task before the voice recognition task, whereas participants who performed the remember voices task before the remember faces task performed the voice recognition task before the face recognition task.

Participants were required to indicate with a button press whether they remembered seeing or hearing each stimulus during the EEG session. If participants had been assigned the right button for a "match" response and the left button for a "nonmatch" response during the EEG session, they were instructed to press the right button for an "old" response and the left button for a "new" response. The other half of the participants received opposite instructions.

Stimuli

The face stimuli consisted of 14 × 18 cm grayscale images depicting a variety of neutral-expression male and female faces across a large age range. The voice stimuli consisted of low-frequency trisyllabic Portuguese words, selected from the Porlex database (Gomes & Castro, 2003). Auditory stimuli audibility was adjusted in each participant to be at a comfortable hearing level to account for individual differences in hearing ability. They were recorded by two female speakers and two male speakers in a sound-attenuated chamber at a 16-bit resolution and a sampling rate of 44,100 Hz. The gender of the face and voice stimuli were held constant within each trial.

Subjective Measures

At the end of the experiment, 5-point Likert scales were administered in which participants were asked to rate how easy or difficult they found to attend to and to ignore the faces and the voices throughout the selective attention tasks (1 = *easy*, 5 = *difficult*).

EEG Recording

Participants were seated in an armchair in a dimly lit room, at a distance of approximately 85 cm from the computer screen. Data were recorded during three runs of 20 trials for each of the three conditions, resulting in 60 trials per condition and 120 segments per stimulus type.

Electrophysiological data were recorded with a BioSemi Active Two 64-channel EEG acquisition system in conjunction with BioSemi ActiView software (Biosemi Inc., Amsterdam, the Netherlands). Signals were amplified and digitized at 1024 Hz with a 16-bit resolution. All electrode offsets were <25 kΩ. Anti-aliasing filters were used and data were band-pass filtered between 0.01 and 100 Hz during data acquisition. EEG recordings were also measured at five external electrodes: bilateral mastoid (LM and RM), right EOG, left EOG, and inferior EOG. In addition, the BioSemi Active Two system uses a feedback loop between two separate electrodes—the common mode sensitive, located between POz and PO3, and the driven right leg electrode, located between the POz and PO4—to drive the reference voltage, such that any electrode could act as the reference. In this study, the average reference was the mean voltage of all 64 channels, calculated offline.

EEG Data Analysis

Preprocessing was conducted through Analyzer software (Brain Vision LLC, Morrisville, NC). Blinks and eye movement artifacts were removed through an independent component analysis. Data were band-pass filtered between 0.5 and 30 Hz. Epochs were created beginning 200 msec before stimulus onset and ending 800 msec afterward and were baseline-corrected (using the −200 to 0 msec time period). Epochs were then cleaned of excessive peak-to-peak deflections, amplifier clippings or other artifacts, using a voltage threshold of 100 mV.

Face and voice trials were separately segmented and averaged, and segments belonging to probe stimuli, as well as to cue stimuli of incorrect trials, were removed from the analysis. ERP statistics were calculated using amplitudes and latencies obtained from each subject, using an 8-msec window centered around each participant's peak amplitude deflection for each component of interest (±4 msec).

Electrode Selection

Responses to faces and responses to voices were collapsed across tasks to select the electrodes with the largest response at the group level among the following electrodes: P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, Pz, PO3, PO4, PO7, PO8, POz, O1, O2 and Oz, for faces; and AF3, AF4, AFz, F1, F2, F3, F4, Fz, FC1, FC2, FC3, FC4, FCz, C1, C2, Cz, CP1, CP2, and CPz, for voices. The most responsive electrodes (provided that they formed a contiguous patch) were then pooled together to create a composite electrode of interest.

Two components were reliably observed for the visual stimuli: the P1 and the N170 components. The P1 component was identified as the first positive deflection appearing between 50 and 150 msec, and the N170 component was identified as the maximal negative deflection appearing between 120 and 220 msec after stimulus onset, at a composite electrode created by pooling P10, P8, and PO8. The right-lateralization of the maximally responsive electrodes for P1 and N170 is consistent with previous studies (e.g., Anguera & Gazzaley, 2012; Zanto, Hennigan, et al., 2010). For quantification of the P1 and N170 components we focused on P1 amplitude and N170 latency, as these have been shown to be the most reliable markers of top–down enhancement and suppression in previous studies using the unimodal visual version of the current paradigm (e.g., Anguera & Gazzaley, 2012; Clapp & Gazzaley, 2012; Zanto, Hennigan, et al., 2010; Gazzaley et al., 2008).

The auditory stimuli elicited an N1–P2 complex. The N1 component was identified as the first negative defection occurring between 80 and 160 msec, and the P2 component was identified as the maximal positive deflection occurring between 160 and 250 msec after stimulus onset, at a composite electrode created by pooling FCz, FC1, FC2, Cz, C1, and C2. Although the auditory N1 was observed and has been shown to be modulated by selective attention (Hillyard, Hink, Schwent, & Picton, 1973), we did not analyze it further, as N1 modulations have only been demonstrated for simpler auditory stimuli (e.g., tone pips), but not for complex trisyllabic voice stimuli as used in this study. In fact, the earliest voice-selective EEG measure has been suggested to occur in the latency range of the P2 (Charest et al., 2009; see also Lattner et al., 2003). For this reason, we only describe the P2 results here and further constrained to P2 amplitude modulations as previously documented (Crowley & Colrain, 2004).

Each of the ranges described for each visual and auditory ERP component were used as initial search boundaries, after which the data were visually inspected and corrections made where necessary on an individual subject basis to ensure that each respective component was properly characterized.

Statistical Analyses

In the selective attention tasks, the percentage of correct responses and RTs pertaining to correct responses were analyzed with a 2 (Age group: younger, older) × 2 (Task modality: visual, auditory) repeated-measures ANOVA (RMANOVA). In the postexperiment recognition task, accuracy (accuracy = [hits + correct rejections]/total possible items) was analyzed with a 2 (Age group: younger, older) × 2 (Stimulus modality: visual, auditory) × 3 (Attentional condition: attend, passive, ignore) RMANOVA. For the subjective measures data analysis, the scores of each question were analyzed with independent-samples *t* tests.

For the EEG data analysis, the latency and amplitude of the visual and auditory components (i.e., P1 and N170 for faces and P2 for voices) were analyzed with a 2 (Age group: younger, older) × 3 (Attentional condition: attend, passive, ignore) RMANOVA. Post hoc two-sided, paired-samples *t* tests were used to test the significance of differences ($p < .05$) between attentional conditions from a priori hypotheses. In all of the analyses, the alpha level was set to .05. A Greenhouse–Geisser correction was applied to the degrees of freedom and significance levels whenever the assumption of sphericity was violated.

To assess whether the extent of neural modulation was positively associated with the extent of behavioral modulation (such that, e.g., the higher the neural enhancement, the higher the recognition enhancement), we calculated one-tailed Pearson correlations between neural and recognition indices of overall modulation (i.e., attend vs. ignore conditions), enhancement (i.e., attend vs. passive conditions), and suppression (i.e., passive vs. ignore conditions). These measures were calculated such that positive values always indicated greater enhancement above baseline or greater suppression below baseline.

RESULTS

Behavioral Results

Selective Attention Tasks

There was a main effect of Age group on accuracy, $F(1, 38) = 4.34$, $p = .044$, indicating that older adults responded less accurately ($M = 91.9\%$, $SD = 7.2$) than younger adults ($M = 95.2\%$, $SD = 4.8$). There was no effect of Task on accuracy, $F(1, 38) = 0.24$, $p = .628$, such that responses were as accurate in the remember faces task ($M = 93.3\%$, $SD = 5.8$) as in the remember voices task ($M = 93.8\%$, $SD = 6.8$). Age group did not interact with this effect, $F(1, 38) = 0.64$, $p = .429$, indicating that this was true for both age groups (Figure 2, left).

There was a main effect of Age group on RTs, $F(1, 38) = 26.50$, $p < .001$, revealing that older adults responded more slowly ($M = 1,053$ msec, $SD = 188$) than younger adults ($M = 809$ msec, $SD = 169$). The effect of Task was significant on RTs, $F(1, 38) = 64.37$, $p < .001$, indicating that responses were faster in the remember faces task ($M = 853$ msec, $SD = 198$) than in the remember voices task ($M = 1,009$ msec, $SD = 207$). Age group did not interact with this effect, $F(1, 38) = 0.03$, $p = .868$, such that it was equivalent across age groups (Figure 2, right).

The average accuracy in the passive task was 99.1% ($SD = 2.3$) for younger adults and 98.4% ($SD = 2.0$) for older adults, and the average RTs were 504 msec ($SD = 109$) for younger adults and 652 msec ($SD = 148$) for older adults.

Postexperiment Recognition Tasks

There was no effect of Age group, $F(1, 38) = 0.98$, $p = .329$, indicating that older adults responded as accurately ($M = 61.7\%$, $SD = 12.1$) as younger adults ($M = 64.2\%$, $SD = 11.2$). The main effect of stimulus modality was

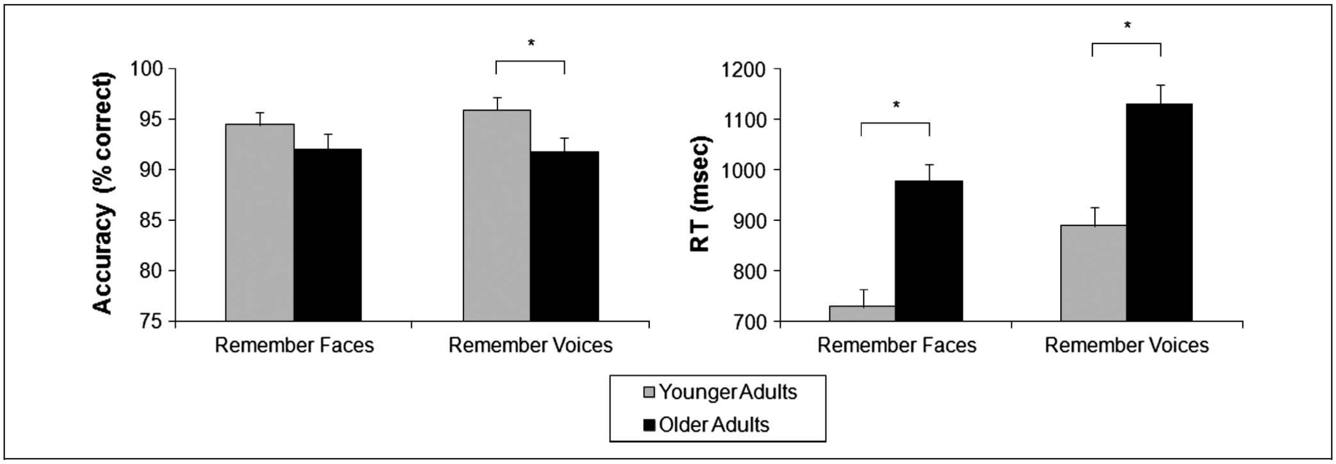

Figure 2. Performance in the selective attention tasks. Left: Mean accuracy and standard errors for younger and older adults. Right: Mean RT and standard errors for younger and older adults. $*p < .05$.

significant, $F(1, 38) = 17.34$, $p < .001$, such that faces were recognized more accurately ($M = 67.3\%$, $SD = 10.8$) than voices ($M = 58.7\%$, $SD = 11.0$). Age group did not interact with this effect, $F(1, 38) = 0.00$, $p = .947$, indicating that this was true for both age groups. There was a main effect of Task, $F(2, 76) = 23.21$, $p < .001$, as well as an interaction between Task and Stimulus modality, $F(1.60, 60.80) = 74.22$, $p < .001$, but no Task × Age Group interaction, $F(2, 76) = 0.04$, $p = .965$, nor Task × Stimulus Modality × Age Group interaction, $F(1.60, 60.80) = 1.80$, $p = .181$. These results indicate that the effect of attentional condition on stimuli recognition varied across stimulus modalities, but not across age groups. For this reason, in what follows, we report the results separately by stimulus modalities.

Face recognition. There was a main effect of Task, $F(1.74, 67.75) = 70.70$, $p < .001$, indicating that face recognition differed across attentional conditions. Planned comparisons indicate that attended faces were significantly better recognized than ignored faces in both younger, $t(19) = 8.41$, $p < .001$, and older adults, $t(19) = 5.92$, $p < .001$. Furthermore, attended faces were significantly better recognized than passively viewed faces in both younger, $t(19) = 6.95$, $p < .001$, and older adults, $t(19) = 5.24$, $p < .001$, and ignored faces were significantly less well recognized than passively viewed faces in younger adults, $t(19) = 2.38$, $p = .028$, but this trend did not reach significance in older adults, $t(19) = 1.27$, $p = .218$ (Figure 3, left).

Voice recognition. There was a main effect of Task, $F(1.69, 65.99) = 18.54$, $p < .001$, indicating that voice recognition differed across attentional conditions. Planned comparisons indicate that attended voices were significantly better recognized than ignored voices in both

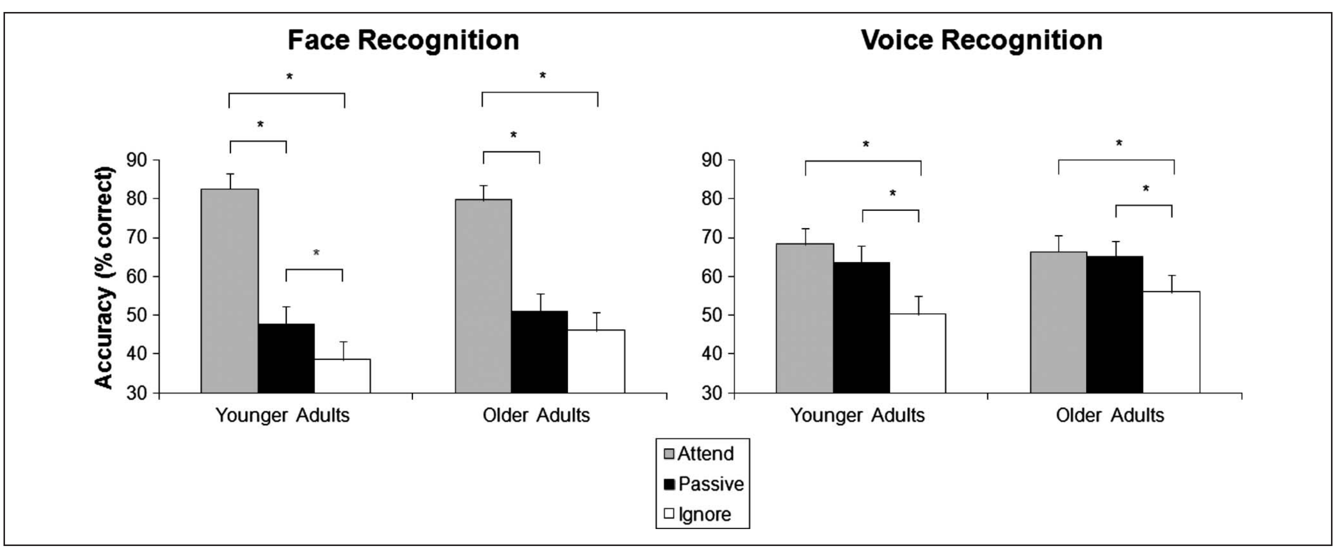

Figure 3. Performance in the postexperiment recognition tasks. Left: Mean accuracy and standard errors for younger and older adults in the face recognition task. Right: Mean accuracy and standard errors for younger and older adults in the voice recognition task. $*p < .05$.

younger, $t(19) = 3.76$, $p = .001$, and older adults, $t(19) = 3.28$, $p = .004$. Moreover, attended voices were recognized as well as passively heard voices in both younger, $t(19) = 1.36$, $p = .189$, and older adults, $t(19) = 0.64$, $p = .530$, whereas ignored voices were significantly less well recognized in both younger, $t(19) = 3.47$, $p = .003$, and older adults, $t(19) = 3.18$, $p = .005$ (Figure 3, right).

Thus, behavioral data showed impaired working memory performance in older adults in both visual and auditory modalities. Furthermore, postexperiment performance suggested distinct recognition profiles in the visual and auditory modalities, but which did not vary with age, that is, age-intact enhanced recognition of attended versus passively viewed faces in the visual modality and age-intact diminished recognition of ignored versus passively heard voices in the auditory modality. There was a trend toward reduced suppression of ignored faces in older adults, but this did not reach significance in the Task × Stimulus Modality × Age Group interaction.

Electrophysiological Results

Visual ERP Measures

Table 1 displays the mean P1 amplitude and mean N170 latency at the composite electrode composed by electrodes P10, P8, and PO8 as a function of age group and experimental condition.

P1. There was a main effect of Age group on P1 amplitude, $F(1, 38) = 4.74$, $p = .036$, such that P1 amplitude was higher for older adults ($M = 2.94$ μV, $SD = 1.37$) than for younger adults ($M = 2.29$ μV, $SD = 1.04$). There was no effect of Task, $F(2, 76) = 1.03$, $p = .361$, as well as no interaction between Task and Age group, $F(2, 76) = 0.59$, $p = .559$, indicating that P1 amplitude was not modulated by attention in either age group.

Table 1. Mean Visual P1 Component Amplitude (μV) and N170 Component Latency (msec) at the Visual Composite Electrode Composed by Electrodes P10, P8, and PO8 as a Function of Age Group and Experimental Condition

	Younger Adults		*Older Adults*	
	M	*SD*	*M*	*SD*
P1 Amplitude				
Attend	2.51	0.93	2.95	1.54
Passive	2.22	0.87	3.13	1.26
Ignore	2.14	1.29	2.74	1.33
N170 Latency				
Attend	149	9	167	12
Passive	151	9	172	21
Ignore	154	19	175	20

N170. There was a main effect of Age group on N170 latency, $F(1, 38) = 22.57$, $p < .001$, indicating that N170 peaked later in older adults ($M = 171$ msec, $SD = 18$) than in younger adults ($M = 151$ msec, $SD = 13$). The effect of Task was significant, $F(2, 76) = 4.38$, $p = .016$, such that N170 latency was modulated by attention, but Age group did not interact with Task, $F(2, 76) = 0.21$, $p = .812$, indicating that the effect of attention on N170 latency was equivalent across age groups (Figure 4). Given this age equivalence, post hoc comparisons of overall modulation, enhancement, and suppression were collapsed across groups, revealing significant overall modulation (attend faces vs. ignore faces), $t(39) = -2.81$, $p = .008$. Relative to the passive task, there was only a slight trend toward enhancement (attend faces vs. passive), $t(39) = -1.74$, $p = .090$, whereas suppression (passive vs. ignore faces) did not reach significance, $t(39) = -1.37$, $p = .177$.

Auditory ERP Measures

Table 2 displays the mean P2 amplitude at the composite electrode composed by electrodes FC1, FC2, FCz, C1, C2, and Cz as a function of age group and experimental condition.

P2. There was no effect of Age group on P2 amplitude, $F(1, 38) = 1.64$, $p = .209$, such that it was equivalent between older adults ($M = 1.31$ μV, $SD = 1.13$) and younger adults ($M = 1.74$ μV, $SD = 1.31$). The effect of Task was significant, $F(2, 76) = 12.59$, $p < .001$, indicating that attention modulated P2 amplitude, but Age group did not interact with this effect, $F(2, 76) = 2.00$, $p = .142$, such that it was equivalent across age groups (Figure 5). Given this age equivalence, post hoc comparisons of overall modulation, enhancement, and suppression were collapsed across groups, revealing significant overall modulation (attend voices vs. ignore voices), $t(39) = 4.98$, $p <$ 001. Although enhancement (attend voices vs. passive) did not approach significance, $t(39) = 1.58$, $p = .123$, there was significant suppression (passive vs. ignore voices), $t(39) = 3.36$, $p = .002$.

To exclude the possibility that the effect observed on P2 amplitude represents a general attentional effect, rather than top–down modulation of auditory sensory processing, we conducted a similar analysis on P2 amplitude at the same auditory composite electrode but in response to visual stimuli. In short, the possibility that the effect on auditory P2 amplitude observed here could simply reflect a general attentional effect arises from the fact that attention—and, in particular, top–down modulation—involves frontal lobe activity (e.g., Zanto, Rubens, Thangavel, & Gazzaley, 2011), which could be observed over similar

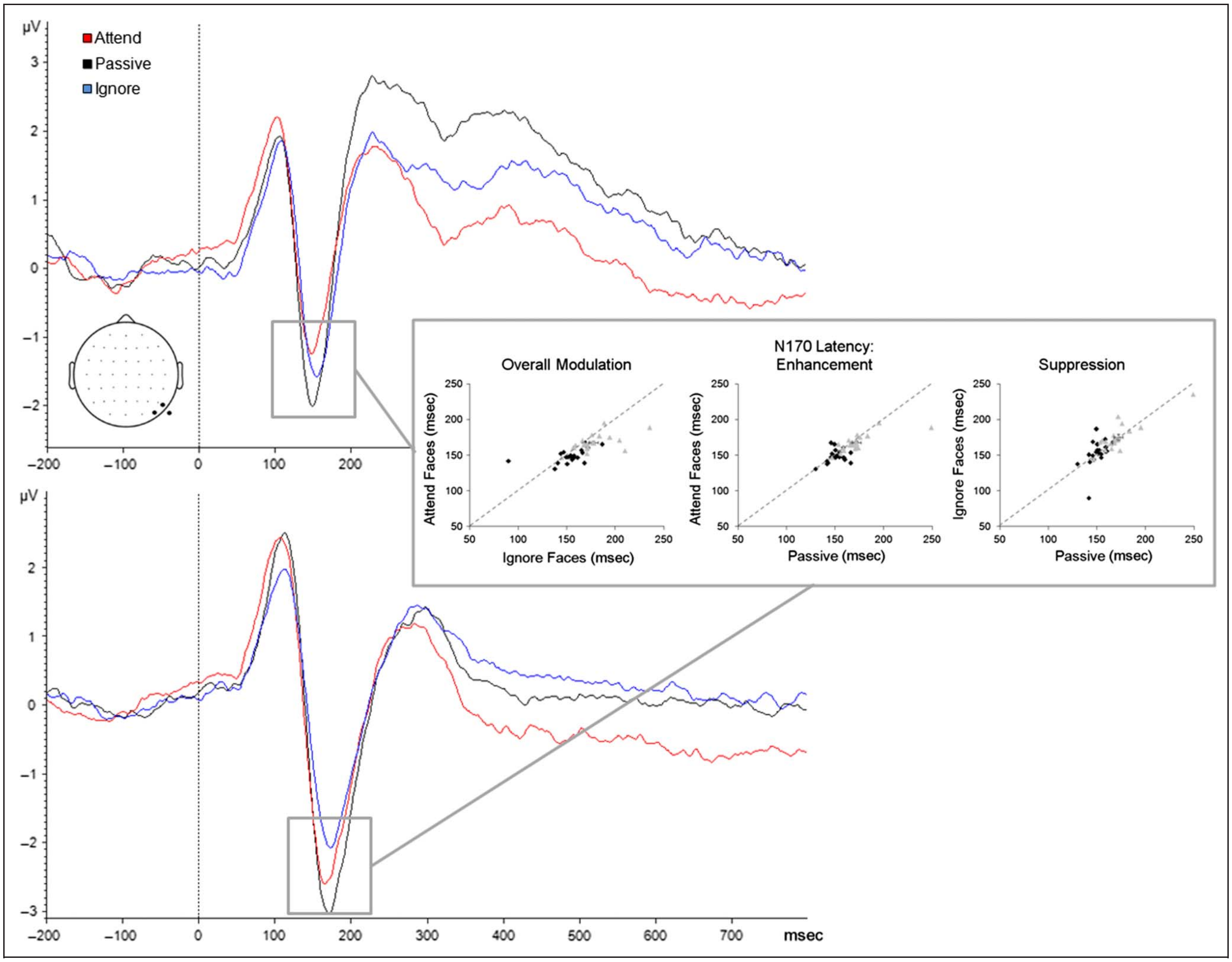

Figure 4. ERPs to faces at the composite electrode composed by electrodes P08, P10, and P8 for younger adults (top) and older adults (bottom). The red line indicates attended faces, the black line indicates passively viewed faces, and the blue line indicates ignored faces. Black diamonds represent younger adults, and gray triangles represent older adults in inset scatter plots. The black diamond with error bars and the gray triangle with error bars represent the mean and *SEM* for younger and older adults, respectively. The unity line references equivalent performance across the different attention manipulations.

frontocentral electrodes as the auditory ERPs. If the effect observed here is a general attentional effect, then a similar effect should be observed on the same frontocentral electrodes for visual stimuli. If, however, the effect observed here truly reflects top–down modulation of auditory sensory processing, then no effect should be observed on the same electrodes for visual stimuli.

Table 2. Mean Auditory P2 Component Amplitude (µV) at the Auditory Composite Electrode Composed by Electrodes FC1, FC2, FCz, C1, C2, and Cz as a Function of Age Group and Experimental Condition

	Younger Adults		*Older Adults*	
	M	*SD*	*M*	*SD*
P2 Amplitude				
Attend	2.07	1.53	1.65	1.05
Passive	1.97	1.08	1.24	1.33
Ignore	1.19	1.15	1.05	0.96

This additional analysis revealed a marginal effect of Age group, $F(1, 38) = 3.53$, $p = .068$, such that there was a tendency for P2 amplitude for visual stimuli at frontocentral electrodes to be higher in older adults ($M = 1.39$ µV, $SD = 1.49$) than in younger adults ($M = 0.68$ µV, $SD = 1.12$). Most important, the effect of Task was nonsignificant, $F(2, 76) = 2.18$, $p = .120$, as was the interaction between Task and Age group, $F(2, 76) = 0.28$, $p = .756$, revealing that P2 amplitude for visual stimuli at frontocentral electrodes was not modulated by attention in either age group (Table 3). This analysis indicates that the suppression of P2 amplitude observed at frontocentral electrodes for auditory stimuli is not a general attentional effect, but rather top–down modulation of auditory sensory processing.

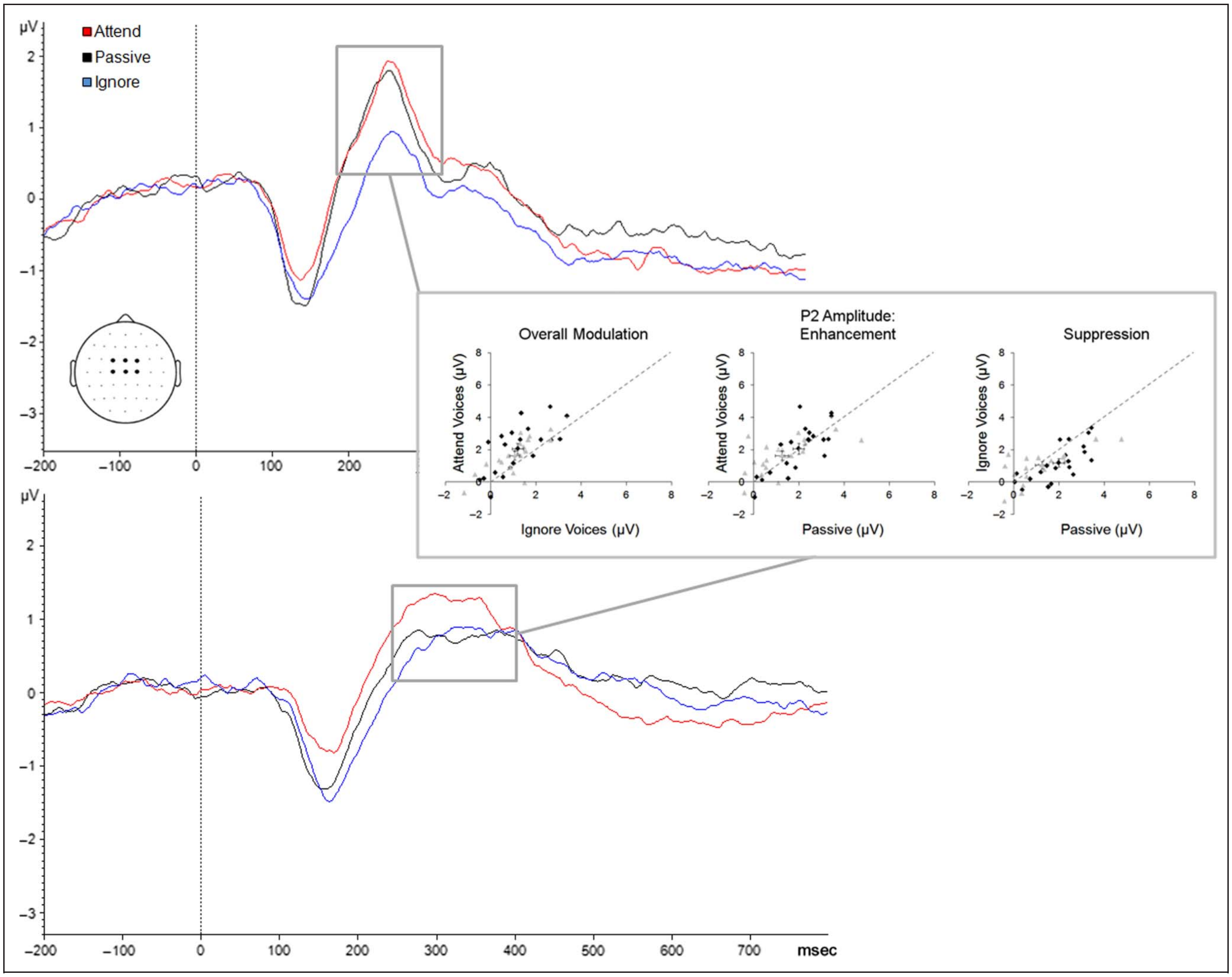

Figure 5. Group-averaged ERPs to voices at the composite electrode composed by electrodes FCz, FC1, FC2, Cz, C1, and C2 for younger adults (top) and older adults (bottom). The red line indicates attended voices, the black line indicates passively heard voices, and the blue line indicates ignored voices. Black diamonds represent younger adults, and gray triangles represent older adults in inset scatter plots. The black diamond with error bars and the gray triangle with error bars represent the mean and *SEM* for younger and older adults, respectively. The unity line references equivalent performance across the different attention manipulations.

Subjective Measures

Younger and older adults did not differ in their ratings of how easy or difficult it was to attend to faces, $t(38) = 0.67$, $p = .505$, or voices, $t(38) = 0.21$, $p = .834$, nor in their ratings of how easy or difficult it was to ignore faces, $t(38) = 1.30$, $p = .201$, or voices, $t(38) = 1.25$, $p = .218$.

Table 3. Mean Visual P2 Component Amplitude (μV) at the Auditory Composite Electrode Composed by Electrodes FC1, FC2, FCz, C1, C2, and Cz as a Function of Age Group and Experimental Condition

	Younger Adults		*Older Adults*	
	M	*SD*	*M*	*SD*
P2 Amplitude				
Attend	0.77	1.25	1.36	1.72
Passive	0.77	1.15	1.60	1.36
Ignore	0.50	0.99	1.21	1.40

Correlations between Neural Modulation and Recognition Performance

As neural modulation in the visual modality was limited to overall modulation and a tendency toward enhancement on N170 latency, correlations with visual behavior were exclusively tested between these neural indices and their counterpart face recognition measures. Similarly, in the auditory modality, significant overall modulation and suppression, but no significant enhancement, were observed on P2 amplitude, and therefore, these neural measures were correlated with their counterpart behavioral voice recognition measures.

There was a trend toward a positive correlation between overall modulation of face recognition and overall

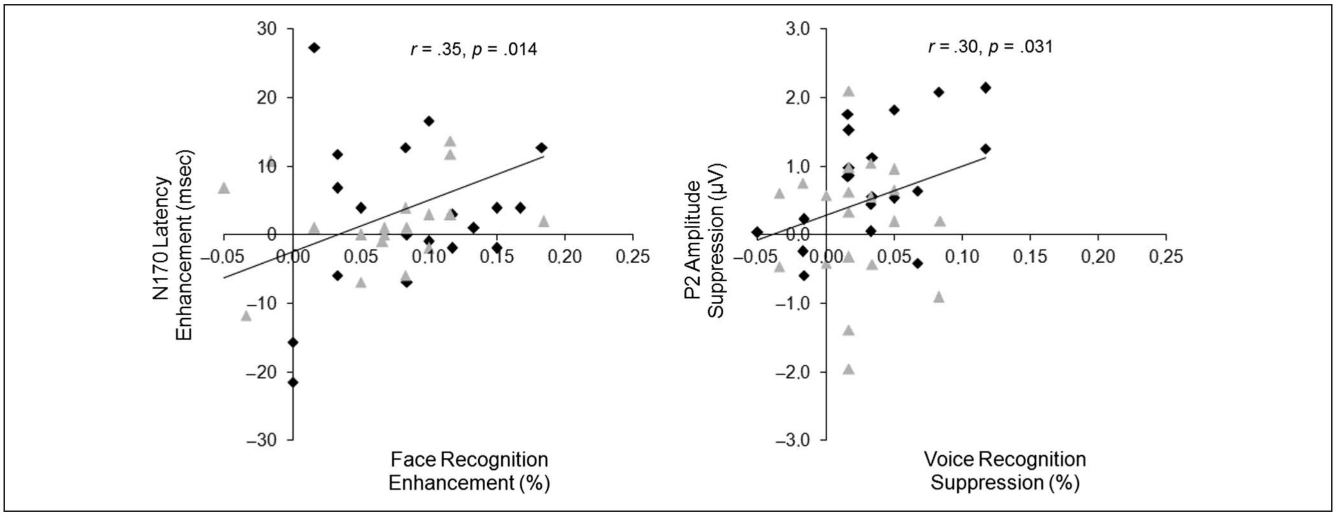

Figure 6. Correlations between neural modulation and recognition performance. Face enhancement is defined as the difference between attend faces and passively view faces conditions. Voice suppression is defined as the difference between passively hear voices and ignore voices conditions. Black diamonds represent younger adults and gray triangles represent older adults.

modulation of visual N170 latency, $r = .22$, $p = .083$. Importantly, face recognition enhancement was positively correlated with N170 latency enhancement, $r = .35$, $p = .014$ (Figure 6, left), indicating that earlier N170 latency when attending to faces relative to passively viewing them was associated with better recognition of attended faces relative to passively viewed faces.

Overall modulation of voice recognition did not correlate with overall modulation of auditory P2 amplitude, $r = .19$, $p = .118$. Notably, however, voice recognition suppression was positively correlated with P2 amplitude suppression, $r = .30$, $p = .031$ (Figure 6, right), such that the lower the P2 amplitude when ignoring voices relative to passively hearing them, the less well distracting voices were recognized relative to passively heard voices.

DISCUSSION

The overarching goal of this study was to investigate top–down modulation in the context of cross-modal selective attention and how it changes with age. At the behavioral level, older adults performed worse than younger adults in the selective attention, delayed-recognition tasks. The analysis of the early visual ERPs, as analyzed in N170 latency measures, revealed an overall tendency for both age groups to exhibit enhancement of visual information in the setting of auditory distraction, but no significant suppression of visual distraction when auditory information was relevant. The analysis of the early auditory ERPs, as measured in P2 amplitudes, revealed suppression of auditory distraction when visual stimuli were relevant, but no significant enhancement of auditory information in the setting of visual distraction. The ERP results mimicked the postexperiment stimulus recognition behavior, and importantly both of these results showed no differences with age. Similarly, there were no age differences in the subjective ratings of how difficult it was to attend to relevant stimuli and to ignore irrelevant stimuli across sensory modalities. Finally, face recognition enhancement was positively correlated with visual enhancement at the neural level, whereas voice recognition suppression was positively correlated with auditory suppression at the neural level.

The observation that older adults generally performed worse than younger adults in the face and voice selective attention, delayed-recognition tasks is consistent with the finding that working memory declines with age (e.g., Rypma & D'Esposito, 2000; Hasher & Zacks, 1988). Despite this behavioral impairment in the working memory tasks, stimulus recognition in the postexperiment long-term memory recognition tasks was age equivalent and, more importantly, there were no age differences as a function of attentional condition. That is, better recognition of attended faces as compared with passively viewed faces in the visual modality and diminished recognition of ignored voices as compared with passively heard voices in the auditory modality were evidenced for both younger and older adults. Thus, long-term recognition findings suggest that stimulus encoding in the presence of cross-modal interference is equivalent across age groups, in agreement with studies showing age-equivalent performance during cross-modal attention (e.g., Guerreiro et al., 2012, 2014; Mishra & Gazzaley, 2013; Hugenschmidt et al., 2009). Note that we did not find strong evidence to support the hypothesis of an asymmetry in cross-modal distractibility with age (Guerreiro et al., 2010, 2013; Guerreiro & Van Gerven, 2011), which proposes that older adults are as vulnerable as younger adults to cross-modal auditory distraction, but more vulnerable than younger adults to cross-modal visual distraction. A weak trend in support of this hypothesis was observed in the postexperiment recognition performance, as suppression of ignored faces (during attention to voices) was significant only in young adults, but not in older adults; however, this did not survive group-level interactions. It is possible that an alternate experimental design with more challenging distractions presented simultaneous, not sequential, to relevant information (Guerreiro et al., 2013; Guerreiro & Van Gerven, 2011) would more strongly support the hypothesis of an asymmetry in cross-modal distractibility with age and remains to be investigated in future studies.

The age-equivalent results in recognition accuracy were paralleled by age-equivalent early ERP component modulations elicited to attended, ignored, and passively perceived stimuli. Furthermore, there were no age differences in how difficult participants rated attending to the visual and auditory stimuli nor in how difficult participants rated ignoring the visual and auditory stimuli. In the following sections, we discuss the top–down modulations of early sensory ERPs separately by modality.

Top–Down Modulation of Visual Processing

The analysis of the visual ERP measures, P1 amplitude and N170 latency, and a comparison with the literature suggest that cross-modal selective attention modulates visual cortical activity to a lesser extent than unimodal visual selective attention. In fact, unlike unimodal visual tasks, where both enhancement and suppression are observed in P1 amplitude (Gazzaley et al., 2008) and N170 latency measures (Gazzaley et al., 2008; Gazzaley, Cooney, McEvoy, et al., 2005), top–down modulation effects in the present cross-modal paradigm were limited to overall modulation and a trend toward enhancement, whereas suppression did not reach significance. Furthermore, in this study these effects were restricted to the face-selective N170 component. Importantly, the only difference between the present task and the task used in previous studies (Gazzaley et al., 2008; Gazzaley, Cooney, McEvoy, et al., 2005) is the sensory modality of irrelevant information, as stimuli presentation setup was equivalent across studies. Postexperiment recognition testing supported the neural findings by showing that attended visual stimuli were better recognized than ignored visual stimuli, as well as better recognized than passively viewed visual stimuli (Wais, Martin, & Gazzaley, 2012; Wais, Rubens, Boccanfuso, & Gazzaley, 2010). Moreover, face recognition enhancement was positively correlated with N170 latency speeding, such that that the greater the neural enhancement, the better the attended faces were remembered relative to passively viewed faces.

The present results therefore indicate that cross-modal selective attention, much like unimodal selective attention, modulates early visual processing, although top–down modulation of visual ERPs appears to be stronger during unimodal selective attention than during cross-modal selective attention. This difference in top–down modulation effects within and across sensory modalities has been explained by the fact that attentional capacity is primarily limited within, but not between, sensory modalities (e.g., Duncan, Martens, & Ward, 1997). By this account, allocating greater resources to relevant information reduces the resources available for processing of irrelevant stimuli in unimodal selective attention conditions, but not necessarily in cross-modal selective attention conditions (e.g., Weissman et al., 2004; but see Macdonald & Lavie, 2011). It is also possible that the sequential presentation of targets and distractors as employed in this study might not have triggered enough competition between relevant and irrelevant information, such that a setting where competition is higher—as when targets and distractors are concurrently presented—might lead to stronger cross-modal attentional effects (Johnson & Zatorre, 2005, 2006; but see Weissman et al., 2004). Future studies should address this possibility by comparing the magnitude of top–down modulation effects during cross-modal selective attention between conditions in which targets and distractors are sequentially presented and conditions in which targets and distractors are concurrently presented.

In terms of aging effects, we found that older adults generally had higher P1 amplitude and slower N170 latency than younger adults. The age-related slowing of N170 latency is consistent with previous studies using a unimodal variant of the present paradigm (Clapp & Gazzaley, 2012; Zanto, Toy, & Gazzaley, 2010; Gazzaley et al., 2008). In contrast, P1 amplitude has been typically shown to be age equivalent (Clapp & Gazzaley, 2012; Gazzaley et al., 2008). Although surprising, an age-related increase in P1 amplitude has also been reported in a number of other studies (for a review, see De Sanctis et al., 2008). Most important, this study showed age-equivalent top–down modulation of visual cortical activity during cross-modal selective attention. That is, younger and older adults alike showed a tendency toward enhancement of visual cortical activity when visual stimuli were relevant in the setting of auditory distraction, whereas suppression of visual cortical activity when visual stimuli were irrelevant during auditory attention did not reach significance in either age group. The age-equivalent top–down modulation of visual cortical processing during cross-modal selective attention observed in this study is consistent with the claim that cross-modal selective attention is intact in aging (Mishra & Gazzaley, 2013; Hugenschmidt et al., 2009).

Top–Down Modulation of Auditory Processing

Top–down modulation of early auditory processing was observed as suppression of auditory distraction when visual information was relevant, but no significant enhancement of auditory information in the setting of visual distraction. Postexperiment recognition testing corroborated these findings by showing that ignored auditory stimuli were less well recognized than passively heard auditory stimuli, whereas attended auditory stimuli were recognized as well as passively heard auditory stimuli. Moreover, there was a positive correlation between voice recognition suppression and P2 amplitude suppression, indicating that the greater the P2 amplitude suppression, the less well the distracting auditory stimuli were recognized relative to passively heard auditory stimuli. The present results corroborate the notion that top–down modulation may be less strongly implemented during cross-modal selective attention than during unimodal selective attention, as only suppression of auditory distraction reached significance in the present cross-modal paradigm. Nevertheless, the finding of significant auditory suppression is in line with the claim that the auditory modality is equipped with powerful inhibition mechanisms to avoid sensory overload from irrelevant information (Čeponienė, Westerfield, Torki, & Townsend, 2008; Näätänen, 1990).

In terms of aging effects, we found that both age groups had lower P2 amplitude to ignored auditory stimuli than to passively heard auditory stimuli, revealing age-equivalent top–down modulation of auditory cortical activity during cross-modal selective attention. These results reveal that the age-related suppression deficit typically found in unimodal visual selective attention (Gazzaley et al., 2008; Gazzaley, Cooney, Rissman, et al., 2005) does not extend to cross-modal attention, such that older adults are able to suppress irrelevant auditory information during visual attention to the same extent as younger adults. This finding is consistent with the age-equivalent vulnerability to cross-modal auditory distraction that is typically observed in irrelevant speech paradigms (e.g., Guerreiro et al., 2013; Guerreiro & Van Gerven, 2011) and in cross-modal Simon tasks (e.g., Guerreiro et al., 2014; Simon & Pouraghabagher, 1978).

Conclusions

This study suggests that top–down modulation is less prevalent during cross-modal selective attention than during unimodal visual selective attention. In fact, in the present cross-modal paradigm with sequential presentation of targets and distractors, top–down modulation of visual processing was observed as a tendency toward enhancement of relevant visual information in the setting of auditory distraction, whereas suppression of visual distraction when auditory information was relevant did not reach significance. Top–down modulation of auditory processing, on the other hand, was observed as suppression of auditory distraction when visual information was relevant, whereas enhancement of relevant auditory information in the setting of visual distraction did not reach significance.

In addition, this study indicates that top–down modulation of visual and auditory neural processing during cross-modal selective attention is independent of age. This finding stands in stark contrast with the typical pattern of age-related deficits in top–down modulation during unimodal visual selective attention, in which older adults have been shown to have a reduced ability to suppress visual distraction (Anguera & Gazzaley, 2012; Zanto, Hennigan, et al., 2010; Gazzaley et al., 2008; Gazzaley, Cooney, Rissman, et al., 2005). Likewise, this finding is not fully in line with the hypothesized age-related asymmetry in cross-modal distractibility, according to which older adults are equally affected by auditory distraction during visual attention but significantly more distracted by irrelevant visual information during auditory attention (Guerreiro et al., 2010, 2013; Guerreiro & Van Gerven, 2011). Instead, this study suggests that when relevant and irrelevant information are presented through different sensory modalities, rather than through the same sensory modality, the neural mechanisms of selective attention remain intact in older age.

Acknowledgments

Maria J. S. Guerreiro was supported by travel grants from the Boehringer Ingelheim Foundation and the Luso-American Development Foundation. We thank Jason Samaha, Melissa Bromley, and Kayla Bowen for their help in assisting with data collection.

Reprint requests should be sent to Maria J. S. Guerreiro, Biological Psychology and Neuropsychology, Department of Psychology, University of Hamburg, Von-Melle-Park 11, D-20146 Hamburg, Germany, or via e-mail: maria.guerreiro@uni-hamburg.de.

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