

# Older Adults Show Impaired Modulation of Attentional Alpha Oscillations: Evidence From Dichotic Listening

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Auditory attention is critical for selectively listening to speech from a single talker in a multitalker environment (e.g., [Cherry, 1953](#)). Listening in such situations is notoriously more difficult and more poorly encoded to long-term memory in older than in young adults ([Tun, O’Kane, & Wingfield, 2002](#)). Recent work by [Payne, Rogers, Wingfield, and Sekuler \(2017\)](#) in young adults demonstrated a neural correlate of auditory attention in the directed dichotic listening task (DDLT), where listeners attend to one ear while ignoring the other. Measured using electroencephalography, differences in alpha band power (8–14 Hz) between left and right hemisphere parietal regions mark the direction to which auditory attention is focused. Little prior research has been conducted on alpha power modulations in older adults, particularly with regard to auditory attention directed toward speech stimuli. In the current study, an older adult sample was administered the DDLT and delayed recognition procedures used by [Payne et al. \(2017\)](#). Compared to young adults, older adults showed reduced selective attention in the DDLT, evidenced by a higher rate of intrusions from the unattended ear. Moreover, older adults did not exhibit attention-related alpha modulation evidenced by young adults, nor did their event-related potentials (ERPs) to recognition probes differentiate between attended or unattended probes. Older adults’ delayed recognition did not reveal a pattern of suppression of unattended items evidenced by young adults. These results serve as evidence for an age-related decline in selective auditory attention, potentially mediated by age-related decline in the ability to modulate alpha oscillations.

**Keywords:** alpha modulation, speech perception, attention, aging, EEG

Listening to a conversation in a crowded or noisy room is a common and challenging auditory situation. Not only is the intended speech difficult to hear but ignoring irrelevant speech is effortful and attention-demanding ([Bregman, 1994](#)). In addition to their age-related declines in hearing ability (e.g., [Committee on Hearing, Bioacoustics, and Biomechanics, 1988](#); [Humes, 1996](#)), older adults tend to have general difficulty inhibiting irrelevant stimuli ([Hasher & Zacks, 1988](#); [Tun et al., 2002](#)). This combination of factors makes crowded and noisy environments more frustrating for older adults than for young adults ([Shinn-Cunningham, 2009](#)). Studies in a laboratory setting show that in such difficult listening situations older adults have to expend greater effort than young adults to achieve similar levels of performance, as evidenced by pupil dilation ([Zekveld, Kramer, &](#)

[Festen, 2011](#)), reaction time (RT; [Hornsby, 2013](#)), and on performance on a secondary task ([Tun, McCoy, & Wingfield, 2009](#)).

[Cherry \(1953\)](#) famously coined the term *cocktail party problem* to describe the situation in which a listener tries to segregate speech from a single talker amid a group of other, irrelevant, talkers. To study the cocktail party problem, he devised the directed dichotic listening task (DDLT), during which listeners were presented with recordings from two talkers over earphones, one presented to each ear, and given cues to indicate to which talker the participant should attend (e.g., a left-facing arrow cued attention to the talker heard in the left ear). Using the DDLT, [Craik \(1965\)](#) found that older adults were more likely to confuse the attended and unattended channels and attributed this pattern to declines in attentional control. Attentional control processes are essential for selection of task-related information and responses ([Milham et al., 2002](#)), and age-related deficits have been well documented in studies of cognitive aging (e.g., [Balota, Dolan, & Duchek, 2000](#)). Such attentional control deficits have been found to exist even after taking into account age-related declines in basic perceptual processing ([Matty, Davis, Bradlow, & Scott, 2012](#)).

One aspect of attentional control is the coordination of processes responsible for inhibiting task-irrelevant information ([Braver & Barch, 2002](#)). Many studies have reported that older adults suffer from a deficit in the ability to inhibit irrelevant stimuli (for a review, see [Lustig, Hasher, & Zacks, 2007](#)), which is especially pronounced in groups that experience age-related hearing loss ([Dey & Sommers, 2015](#)). In these cases, older adults report exerting more effort to achieve a similar level of listening performance

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than young adults (Tun & Lachman, 2008; Tun & Wingfield, 1995). The exertion of effort has downstream consequences, as effort exerted while listening to perceptual stimuli leaves fewer resources available to encode that information into long-term memory (McCoy et al., 2005). In the case of dichotic listening, a failure to successfully inhibit irrelevant speech could result in increased intrusions from the unattended channel.

A technique for measuring the downstream effects of inhibitory processing is delayed recognition (e.g., Jacoby, Shimizu, Velanova, & Rhodes, 2005). For example, in a study in which young and older adults read stories that contained distracting information, Thomas and Hasher (2012) reported that young adults showed poorer memory than older adults for those same distracting words on a delayed recognition test. The authors held that the effect of young adults' suppression of distracting information during story reading transferred to delayed recognition, whereas older adults' better memory for distracting items indicated a deficit in inhibition. Evidence of suppression of a distractor item during a listening task would be indicated by impaired delayed memory for that distractor item. Such impaired memory represents a transfer of the effects of inhibition from one context (e.g., listening), to another (e.g., long-term memory).

Using a form of the DDLT task, Payne et al. (2017) presented young adults with recognition probes and asked them to indicate whether the probe was presented in the to-be-attended ear. Perceptual dampening of irrelevant perceptual stimuli is known to be correlated with alpha-band activity measured via electroencephalography (EEG; Payne & Sekuler, 2014). Increased power in the alpha band (8–14 Hz) is associated with increased ignoring of an irrelevant stimulus (e.g., Wöstmann, Schröger, & Obleser, 2015), increased working memory demands (e.g., Obleser, Wöstmann, Hellbernd, Wilsch, & Maess, 2012), and attentional control (e.g., Shinn-Cunningham & Best, 2008). Spatial lateralization of auditory attentional control in the DDLT is marked by interhemispheric differences in EEG alpha power (Kerlin, Shahin, & Miller, 2010; Frey et al., 2014) and is believed to reflect suppression of the unattended auditory speech stream (Chait, de Cheveigné, Poeppel, & Simon, 2010; Choi, Wang, Bharadwaj, & Shinn-Cunningham, 2014; Zion Golumbic et al., 2013).

Payne et al. (2017) found that young adults' successful filtering of unattended speech was concurrent with modulation of power in the alpha band during encoding. Alpha modulation was found at two different locations, a right lateral frontotemporal and a central parietal site. Young adults performed well on the task but were not perfect—they produced false alarms to words from the unattended ear at a higher rate than to new, extralist words. Young adults also exhibited a right ear advantage for the spoken material, indicated by higher hit rates, lower false alarm rates, and faster response latencies on correct responses. Consistent with this clear right ear advantage, alpha modulation at the right lateral frontotemporal and central parietal sites was greatest when participants were cued to attend to the right ear. Also, on delayed recognition, young adults had good memory for words from the attended side, but poorer than chance memory for words from the unattended ear. This below-chance recognition of unattended items suggests that an outcome of ignoring during the DDLT is suppressed representation of unattended information, consistent with analogous effects of inhibition that have been observed in young adults in the visual modality (e.g., Thomas & Hasher, 2012).

The question of whether older adults show modulation of alpha power attendant to filtering nontarget stimuli to the same extent as young adults remains relatively unsettled. In the visual modality, prior work has suggested that, as compared to young adults, older adults have diminished alpha modulation following a spatial cue during tasks of target detection (Hong, Sun, Bengson, Mangun, & Tong, 2015) and change detection (Vaden, Hutcheson, McCollum, Kentros, & Visscher, 2012). However, also with visual stimuli, it has been reported that older adults have intact modulation of alpha relative to young adults in response to a retro-cue during memory retention (Mok, Myers, Wallis, & Nobre, 2016), and in response to a spatial cue that remains visible to participants in a delayed match-to-sample task (Leenders, Lozano-Soldevilla, Roberts, Jensen, & De Weerd, 2016). As a further complication, Sander, Werkle-Bergner, and Lindenberger (2012) found that during the retention period of a delayed match-to-sample task, both older and young adults' EEG showed spatial cue-related alpha modulation at lower memory loads; however, only young adults' EEG showed modulation at higher memory loads. Unfortunately, in most of these studies, behavioral performance was at ceiling levels for young and older adults or did not differ between older and young adults, making it impossible to discern if modulation of alpha activity is a necessary correlate of task success. After all, it is known that young and older adults could have equivalent performance on a behavioral task but may engage different cognitive processes and recruit different neurobiological mechanisms to achieve similar levels of performance (e.g., Della-Maggiore et al., 2000). In addition, these studies were conducted with visual stimuli, which is easier for researchers to correct for age-related perceptual degradation (e.g., glasses, contact lenses). As a result, work in vision may not generalize to an auditory modality, particularly speech (Weisz, Hartmann, Müller, Lorenz, & Obleser, 2011).

In addition to our focus on age-related effects pertaining to alpha power and modulation during encoding of dichotically presented stimuli, we were also interested in how short-term recognition probes during the DDLT would evoke responses from the brains of young and older adults. As reported by Danker et al. (2008), and others (for a review, see Rugg, 1995), recently presented words evoke more positive event-related potentials (ERPs) than new words, an effect that has been termed the "ERP old-new effect." The DDLT utilized by Payne et al. (2017) is a short-term recognition task, although probes have the additional categorization of being "new," "attended," or "unattended," as opposed to simply "old" and "new." In this task, participants report "yes" or "no" as to whether the probe was presented in the to-be-attended channel. Little work has examined the extent to which attending to or ignoring a word during dichotic encoding affects ERPs. We wished to examine whether older adults' like young adults' ERPs would distinguish between probes that were attended, unattended, or new during the DDLT.

In the current study, we recruited a group of 19 older adults with clinically normal hearing to the same dichotic listening situation that was used by Payne et al. (2017). We then compared their performance to what had been observed in the young adult sample by Payne et al. (2017). Using the same stimuli and procedures as used by Payne and colleagues in their study of young adults, older adult participants listened to simultaneous dichotically presented speech streams (i.e., one stream to each ear), preceded by a cue to

attend to the left or right ear. Short-term memory (STM) for the content of the to-be-attended ear was assessed immediately following the speech stream with a recognition probe. Following the dichotic task, participants completed a delayed recognition test for all words, both to-be-attended and unattended words, that had been presented in the study. Performance was assessed and compared to young adults in four ways: (a) alpha modulation during dichotic listening, (b) behavioral responses and response latencies to the short-term recognition probe, (c) ERPs to the short-term recognition probe, and (d) behavioral responses and latencies during delayed recognition. First, we sought to examine whether older adults' performance, like young adults', would also be associated with a pattern of alpha modulation. Second, we wished to test whether the indirect effect of attentional suppression on delayed recognition would generalize to older adults, or whether older adults would fail to show transfer of the effects of inhibition because of an inhibitory deficit.

## Method

### Participants

The current study was approved for human participants by the Brandeis University Institutional Review Board. Nineteen older adults gave written informed consent and were paid for participation. Of these, four participants were excluded from our analysis because of excessive EEG artifacts (epoch rejection rate >50%). The age range of the remaining 15 participants was from 67–83 years ( $M = 75.40$ ,  $SD = 4.34$ ) and seven were female. All were right-handed as determined by the Edinburgh Handedness Inventory (Oldfield, 1971) and had normal or corrected-to-normal visual acuity as determined by a minimum angle of resolution chart (ETDRS 2000 Series 2, [www.good-lite.com](http://www.good-lite.com)).

The young adults reported by Payne et al. (2017) had a mean pure tone threshold average of 3.08 dB HL ( $SD = 4.61$ ) across 500, 1,000, and 2,000 Hz, with no significant difference in acuity between the two ears,  $t < 1$ , ns. The older adult participants in this study had a mean better-ear PTA of 13.92 dB HL ( $SD = 4.96$ ) and had no significant difference in acuity between the two ears,  $t(13) = 1.16$ ,  $p > .26$ . Although the older adults had poorer hearing acuity than the young adults, all fell within a range defined as clinically normal hearing for speech (PTA <25 dB HL; Mueller & Hall, 1997).

Working memory was also measured for both young and older adults using the Reading Span task (Daneman & Carpenter, 1980). As would be expected (Salthouse, 1994), the older adults had lower average span scores than young adults (young  $M = 2.39$ , older  $M = 1.45$ ),  $t(27) = 3.40$ ,  $p < .01$ . All participants were native English speakers with no self-reported history of stroke, Parkinson's disease, or other neurological disorder that might affect task performance.

### Stimuli and Apparatus

A total of 689 monosyllabic words spoken by a male native speaker of American English were recorded using an Audio Technica AT2045 microphone and SoundEdit software (Macromedia, Inc., San Francisco, CA). Recordings were digitized using a Presonus Audiobox USB audio interface at a sampling rate of 44.1 kHz.

A cosine-squared amplitude ramp of 5-ms rise time was applied to the beginning and end of each word to avoid the popping noise from sudden onsets or offsets. Root-mean square amplitude was equated for all stimuli and leveled to 65 dB SPL.

The 689 words were divided into three groups that were balanced for Kuèera-Francis word frequency (Kucera & Francis, 1967) and assigned to one of the three experimental conditions (Attended, Unattended, New). In each trial of the DDLT, two streams of four words were presented simultaneously, one stream to each ear, through Etymotic Research ER1 insert earphones. Durations for the spoken words were between 422 and 758 ms ( $M = 617$  ms,  $SD = 72$  ms). Stimuli were concatenated into 2 streams of 4 words (i.e., left and right), and synchronized so that each word pair began simultaneously at 0, 800, 1600, and 2400ms.

Electroencephalographic (EEG) signals were recorded from the scalp using a high-density, 129-electrode array (Electrical Geodesics Inc., Eugene OR) and high-impedance amplifiers. All channels were adjusted for scalp impedance <50kΩ. Sensor signals were sampled at 250 Hz with a 0–125 Hz analogue bandpass filter, and stored for offline analysis. Bipolar periocular channels were recorded from above and below each eye, and from a location near the outer canthus of each eye.

### Procedure

Each participant completed one experimental session that included the DDLT phase followed by a Delayed Recognition phase.

**DDLT.** Figure 1 illustrates the DDLT procedure. Each participant completed 210 trials. The first 18 trials were practice trials that were not included in further analysis, resulting in 192 final trials. Participants were cued to attend to the left ear on half of these trials; on the remaining trials they were cued to attend to the right ear. The order of cues was randomly intermixed. For each trial, a visually displayed arrow presented for 0.5 s directed participants to attend to either their right or left ear. Then, 900–1100 ms ( $M = 1000$ ) later, simultaneous streams of four words were presented to the right and left ears through insert earphones. The duration of each four-word stream was 3200 ms. In order to

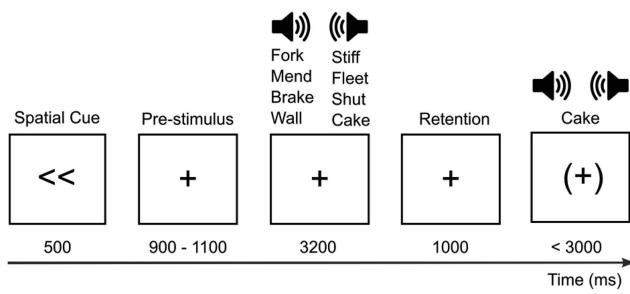


Figure 1. Schematic diagram illustrating the directed dichotic listening task (DDLT) trial event structure. Each trial began with a fixation cross that oriented the participant to the region of the computer display at which the trial's cues would be centered. An arrow cued the subject to attend to either their right (>) or left (<) ear. Then, two simultaneous streams of four spoken words were presented, one stream to each ear. After a brief retention interval, a probe word was presented binaurally. Participants reported via keyboard key press whether or not the probe word had been a member of the to-be-attended word stream.

generate the needed set of paired simultaneous, four-word streams, words were presented three times each across the entire DDLT. Half of these words were only presented in attended streams, and the other half were presented only in unattended streams. The order of attended and unattended word-pair presentations was randomly shuffled for each participant, with the constraint that all word pairs had to be presented in each condition before a given word could be repeated.

Following a brief, 1000 ms retention period, parentheses were displayed around the fixation cross and a single probe word was presented binaurally. For the 96 attend left trials and 96 attend right trials respectively: half of the probes ( $N = 48$ ) were target words from the attended stream (target), 24 were from the unattended stream (unattended probe) and 24 were new words (new probe) that were otherwise not presented during DDLT. The order of target, unattended, and new probe trials was randomized. If the probe was from the attended or an unattended stream, it was equally likely to have appeared at each of the four positions in that trial's word set.

Participants rested two fingers from their right hand on a computer keyboard and responded via a key press to signal whether the probe had or had not been in the current trial's attended stream. Participants had up to three seconds to make a response and were instructed to respond as quickly and as accurately as possible. During the 18 practice trials, feedback was provided after each trial in the form of a green fixation cross for correct responses (attended hit, unattended correct rejection, or new correct rejection) or red for incorrect responses (attended missed, unattended false alarm, or new false alarm). In each case the color was displayed for a 600 ms feedback interval. No feedback was given during the remaining trials.

**Delayed recognition.** Delayed recognition instructions began after DDLT trials, and after the EEG cap had been removed. The time between the end of DDLT trials and the start of delayed recognition ranged from three to seven minutes ( $M = 4$  min). Participants completed the Delayed Recognition phase in less than 10 min. During delayed recognition, words were presented binaurally through the insert earphones. The recognition test was comprised of 120 "old" words randomly drawn from the DDLT trials and 72 "new" words that were not previously heard in the experiment presented in random order. To distinguish the effects of attention during dichotic listening from the effects of attention to a single probe word, whether a word was used as a probe in the earlier DDLT was systematically varied. There were 24 old words from each of the following five categories: Words from the attended stream that had not served as probe words, words from the attended stream that had served as probe words, words from the unattended stream that had not served as probe words, words from the unattended stream that had served as probe words, and words that had been presented as new probes. Participants rested two fingers from their right hand on a computer keyboard. Following each word, the question, "Old or New?" was displayed on the computer screen. Participants were instructed to respond "Old" to any word that was presented in the DDLT phase of the experiment, regardless of whether it was attended or not. They had up to three seconds to make a response and were instructed to respond as quickly and as accurately as possible. The attended words and unattended words were counterbalanced for whether they had been

presented to the left or right ear, and the position they had held within the stream.

## Behavioral Analysis

**DDLT.** For the DDLT, participants' performance was assessed via hit rates to probes of attended items (attended hit) and false alarm rates to probes that were new (FA new) and from the unattended stream (FA unattended). In addition, we examined participants' latencies to correct responses which included attended hits, new correct rejections (CR new), and unattended correct rejections (CR unattended). To attenuate the undue influence of outliers on mean latencies, latencies outside 2.5 standard deviations of the mean for each condition and each participant were considered outliers and excluded from analysis. Further, to minimize the chance that overall response latency differences (e.g., older adults being slower) would affect our interpretation of group by condition interactions (Faust, Balota, Spieler, & Ferraro, 1999) we transformed latencies to  $z$ -scores relative to each participant's overall mean latency.

**Delayed recognition.** The delayed recognition task was meant to assess indirect effects of auditory attentional control processes on words during the DDLT. We hypothesized that words that served as probes during the DDLT might be remembered better because of their monaural presentation and additional processing at the time of short-term recognition. In order to control for this potential concern we limited our analysis only to words that were not probed during the DDLT. Participants' delayed recognition memory sensitivity was measured using  $d'$  (Green & Swets, 1988), which was calculated as the difference between  $z$ -transformed false alarm rates to new items and either  $z$ -transformed hit rates to attended items or unattended items. This yielded two  $d'$  estimates:  $d'$  attended—an index of participants' ability to distinguish attended words from new items, and  $d'$  unattended—an index of the extent to which participants distinguished between unattended words and new items. Both  $d'$  estimates were calculated using the same false alarm rate, but different hit rates. To avoid undefined values of  $d'$  when hit or false alarm rates equaled 1.00 or 0.00, we applied the log-linear rule recommended by Hautus (1995). Latencies to correct responses included attended hits, unattended hits, and correct rejections of new words and were transformed to  $z$ -scores and screened for outliers as described in the DDLT section.

## EEG Analysis

EEG signals were preprocessed using the EEGLAB toolbox (Delorme & Makeig, 2004) for MATLAB (The Mathworks, Inc., Natick, MA). The recorded signals were rereferenced to the grand average voltage. A 0.5-Hz Butterworth high-pass filter and a 60 Hz Parks-McClellan notch filter were applied. Trial epochs were segmented from -2.2 to +8.2 s surrounding the onset of the dichotic stimuli. An initial visual inspection was performed to remove epochs containing gross artifact and to identify bad channels. Bad channels that extended more than 10% of trials were excluded from independent components analysis (ICA). The ICA was performed with EEGLAB's extended infomax ICA decomposition. Components clearly containing blinks, muscle artifacts, eye movements, electrical heartbeat or singular artifacts were manually

identified and subtracted from the data. Bad channels were then interpolated using EEGLAB's spherical spline interpolation. A final visual inspection was performed to reject any remaining epochs with artifacts.

Finally, incorrect trials were also excluded from analysis. The number of artifact-free, correct trials remaining totaled 2,121 trials for older adults ( $N = 15$ ) and 2,025 trials for young adults ( $N = 14$ ) in the Payne et al. (2017) study. All subsequent analyses and plotting were performed using the FieldTrip toolbox (Oostenveld, Fries, Maris, & Schoffelen, 2011) for MATLAB.

**Induced alpha power.** Induced (i.e., nonphase locked) time-frequency power during DDLT was computed using the following method: Separately for every subject, electrode, and condition, the ERP was calculated and this evoked (phase-locked) activity was subtracted from the EEG for each trial (Kalcher & Pfurtscheller, 1995). Following this single trial subtraction of the ERP, time-frequency representations were computed using Morlet wavelets with a width of four cycles per wavelet at center frequencies between 1 and 40 Hz, in 1 Hz steps. Alpha amplitude was calculated as the average power in the frequency range of 8–14 Hz.

**Attend right versus attend left lateralization.** To establish the effect of directional attention on alpha power, the normalized difference between attend right and attend left trials was compared to zero with a data-driven, nonparametric clustering approach (Maris & Oostenveld, 2007). For each participant, alpha amplitude for attend right and attend left trials was averaged separately and then normalized by calculating attendRight-attendLeft/attendRight + attendLeft. First, using the same approach as for young adults (Payne et al., 2017), a dependent samples  $t$ -value was calculated for the entire dichotic epoch from 0 to 3200ms. Then, to reveal any changes in time that might differ between young and older adults, a dependent samples  $t$ -value was calculated at each electrode for 800-ms epochs beginning prestimulus onset and extending through the duration of the dichotic presentation. All comparisons for which the  $t$ -value exceeded the  $p < .05$  significance level were clustered based on spatial adjacency. To be considered a cluster, a minimum of two adjacent sensors with a  $t$ -value exceeding the significance threshold was required. Then for each cluster, the  $t$ -values of its member electrodes were summed, giving a cluster score that reflected both the extent of the cluster in space and the magnitude of the difference between the conditions. A reference distribution of test statistics was generated by randomly permuting the data across the lateralization index and zero, computing such scores for each resulting cluster, and taking the largest such cluster score on each of 1,000 permutations. Where cluster-wise  $p$  values are reported, they came from comparisons between the empirically obtained cluster score and the permuted reference distribution. A difference between the lateralization index and zero was deemed significant if less than 5% of the proportion of randomized values exceeded the observed test statistic.

**Young versus older adults.** Topographic maps of alpha power, averaged across attend-right and attend-left trials, were generated for 800-ms epochs beginning prestimulus onset and extending through the duration of the dichotic presentation (Figure 4, top row). These maps illustrate the consistency of alpha power throughout the dichotic presentation in both young and older adults. Given the minimal spatiotemporal changes in alpha activity seen during dichotic listening, alpha power was averaged within

each of the prestimulus (−800 to 0 ms) and peristimulus (0 to 3,200 ms) epochs for statistical comparison. To establish age-related effects on alpha modulation, an independent samples  $t$ -value for the mean amplitude of alpha power was calculated at each electrode. All comparisons for which the  $t$ -value exceeded the  $p < .05$  significance level were clustered based on spatial adjacency. Then for each cluster, the  $t$ -values of its member electrodes were summed, giving a cluster score that reflected both the extent of the cluster in space and the magnitude of the difference between the younger and older adults. A reference distribution of test statistics was generated by randomly permuting the data across young and older adults, computing such scores for each resulting cluster, and taking the largest such cluster score on each of 1,000 permutations. Where cluster-wise  $p$  values are reported, they came from comparisons between the empirically obtained cluster score and the permuted reference distribution. A difference between young and older adults' mean alpha was deemed significant if less than 5% of the proportion of randomized values exceeded the observed test statistic.

Grand average time-frequency representations were created by averaging across participants and across the electrodes identified as part of the cluster.

**ERPs.** ERPs evoked by the presentation of probe words were used to investigate possible differences in the evoked response between old and new words. The artifact-free, correct trials were low-pass filtered at 30 Hz and baseline corrected using the 200-ms interval preceding the onset of the probe word. ERPs time-locked to the onset of the probe word were generated for each participant by averaging across trials for each of the three probe types (attended, unattended, and new).

To determine an overall old/new effect, the ERP for attended words (old) was first compared to the combination of new and unattended probe words (both considered new). The ERP to attended words was then compared to new and unattended probes words separately to investigate any differences in topography or magnitude between the two comparisons. The clustering approach (Maris & Oostenveld, 2007) described earlier, in the section on alpha power (above), was used for the three comparisons (attended vs. combination of unattended and new, attended vs. new, and attended vs. unattended) with the old/new epoch defined as 300 to 500 ms postprobe onset (Rugg & Curran, 2007). Grand average ERPs were created by averaging across participants and across the electrodes that were significantly different between the old (attended) and new (combined unattended and new) conditions.

## Results

### Behavior

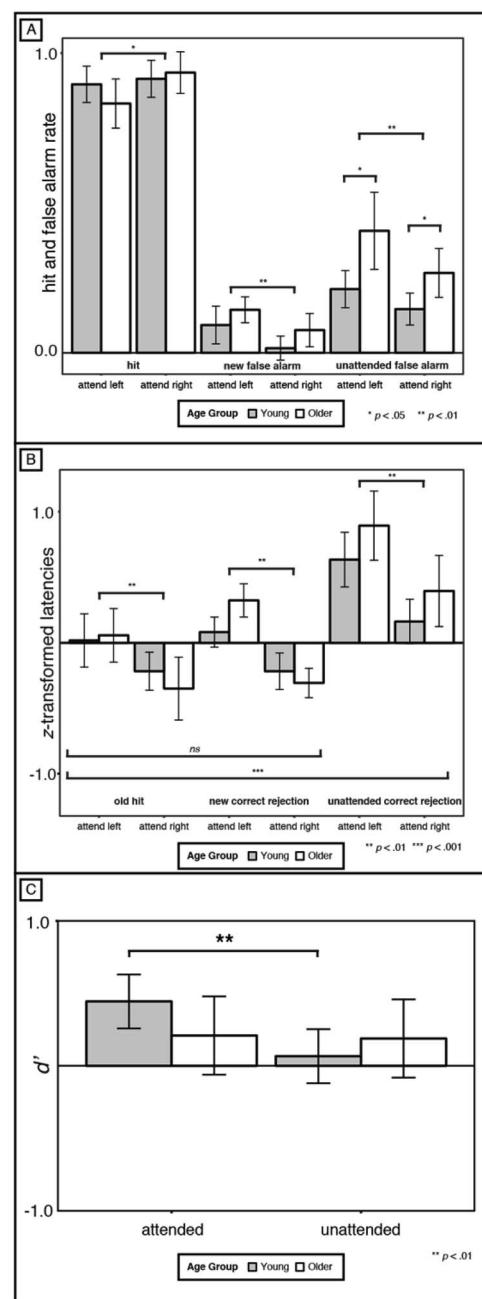
Unless otherwise indicated, we only report effects that were significant at the  $p < .05$  significance level and were not involved in a higher-order of interaction. If an interaction proved to be significant, we used post hoc  $F$  tests that incorporated the Bonferroni correction for reduction of Type I error. Mauchly's test of sphericity and Levene's test for homogeneity of variance were also calculated. If the assumption of sphericity was violated, the Greenhouse-Geisser correction for mean squared error (MSE) and

degrees of freedom was applied. If homogeneity of variance was violated, degrees of freedom were adjusted.

**DDLT.** Participants' performance is given in Figure 2A, which depicts the hit rates to probes that had been presented in the attended channel, false alarms to new probes, and false alarms to probes that had been presented in the unattended channel. Older and young adults had equivalently high hit rates and low false alarm rates to new probes. However, older adults had elevated false alarm rates to probes from the unattended channel relative to young adults. A 3 (response: attended hit, new false alarm, unattended false alarm)  $\times$  2 (attend direction: left, right)  $\times$  2 (age: young, older) mixed-model repeated-measures analysis of variance (ANOVA) revealed a significant Response  $\times$  Age interaction,  $F(1.40, 37.83) = 5.03$ ,  $\eta_p^2 = 0.16$ ,  $p < .05$ .  $F$  tests revealed that age group differences were not significant on attended hits,  $F < 1$ , ns, or new false alarms,  $F(1, 27) = 3.48$ ,  $\eta_p^2 = 0.11$ ,  $p = .07$ , but were significant on unattended false alarms,  $F(1, 27) = 7.45$ ,  $\eta_p^2 = 0.22$ ,  $p = .01$ . The ANOVA also revealed a significant interaction between attend direction and response,  $F(1.49, 40.23) = 9.58$ ,  $\eta_p^2 = 0.26$ ,  $p < .001$ .  $F$  tests revealed that when attending to the right ear as opposed to the left ear, participants had greater hit rates,  $F(1, 27) = 7.18$ ,  $\eta_p^2 = 0.21$ ,  $p < .05$ , lesser new false alarm rates,  $F(1, 27) = 9.71$ ,  $\eta_p^2 = 0.27$ ,  $p < .01$ , and lesser unattended false alarm rates,  $F(1, 27) = 8.72$ ,  $\eta_p^2 = 0.24$ ,  $p < .01$ . This pattern of right ear advantage was equivalent for both age groups, as neither the main effect of attend direction nor the interaction of attend direction and response significantly interacted with age.

$Z$ -transformed latencies to correct responses are given in Figure 2B, which shows that young and older adults were significantly slower to reject an unattended probe than they were to reject a new probe or to endorse an attended probe. A 3 (response: attended hit, new correct rejection, unattended correct rejection)  $\times$  2 (attend direction: left, right)  $\times$  2 (age: young, older) mixed-model repeated-measures ANOVA did not reveal a significant Response  $\times$  Age interaction,  $F(1.42, 38.28) = 2.03$ ,  $\eta_p^2 = 0.07$ ,  $p = .16$ , but did reveal significant effects of response,  $F(1.42, 38.28) = 45.28$ ,  $\eta_p^2 = 0.63$ ,  $p < .001$ , and attend direction,  $F(1, 27) = 51.15$ ,  $\eta_p^2 = 0.65$ ,  $p < .001$ .  $F$  tests revealed that correct rejections to unattended probes were slower than attended hits,  $F(2, 54) = 8.68$ ,  $p < .001$ , and correct rejections to new probes,  $F(2, 54) = 7.34$ ,  $p < .001$ , which did not significantly differ from one another,  $F(2, 54) = 1.25$ ,  $p = .65$ . The significant effect of attend direction was consistent with the right ear advantage observed in hit and false alarm rates, where  $z$ -transformed latencies to correct responses were faster when attending right ( $M = -.09$ ) than when attending left ( $M = .34$ ). ANOVA did reveal a significant main effect of age,  $F(1, 27) = 4.11$ ,  $\eta_p^2 = 0.13$ ,  $p = .05$ , which in the case of  $z$ -transformed latencies reflects greater within-subjects variability between groups (Faust et al., 1999). Older adults' subject-level standard deviations were greater ( $SD = 367$  ms) than those of young adults ( $SD = 255$  ms).

**Delayed recognition.** Delayed recognition to words that were not probed during the DDLT were assessed by examining  $d'$  for words that were attended and unattended, relative to new items. The results are shown in Figure 2C. Discriminability as measured by  $d'$  was low overall, attributable to moderately high false alarm rates (young  $M = .38$ ,  $SD = .16$ ; older  $M = .42$ ,  $SD = .19$ ), low hit rates to attended items (young  $M = .54$ ,  $SD = .13$ ; older  $M = .48$ ,  $SD = .22$ ), and low hit rates to unattended items (young  $M =$



**Figure 2.** Behavioral results from the older adults of the current study and young adult data reported by Payne et al. (2017). Panel A indicates hit and false alarm rates during the directed dichotic listening task (DDLT). Panel B indicates  $z$ -transformed latencies to correct responses during the DDLT. Panel C indicates sensitivity ( $d'$ ) during delayed recognition to attended and unattended words that were not probed during the DDLT. Significance values in Panels A and B denoted by asterisks were obtained from post hoc  $F$  tests applying the Bonferroni correction that were qualified by a higher order interaction. Error bars indicate 95% confidence intervals around the mean.

.41,  $SD = .12$ ; Older  $M = .48$ ,  $SD = .24$ ). That said, the young adults from Payne et al. (2017) showed greater memory discriminability for words that were attended rather than unattended. To examine this pattern in older and young adults, we performed a

planned comparison on older adults'  $d'$  and found no significant difference between hits that were attended and unattended  $t(14) = .14, p = .90$ . A similar comparison for young adults showed that the young did differ between attended and unattended items,  $t(13) = 3.10, p < .01$ . Young adults' sensitivity for unattended items was likely so poor because of their low unattended hit rate. In fact, young adults' unattended hit rates were significantly below chance,  $t(13) = 2.90, p = .01$ , indicative of a transfer of the effects of inhibition from the DDLT to delayed recognition. Similar analyses on  $z$ -transformed response latencies did not reveal any significant effects.

## EEG and ERPs

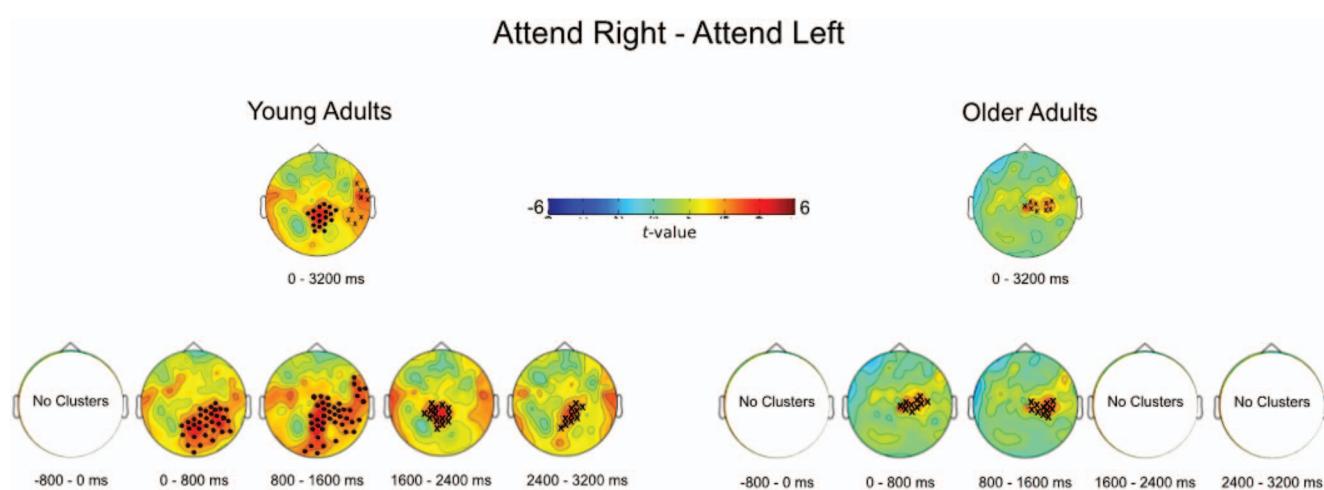
### Alpha power.

**Attend right versus left lateralization.** To establish the effect of directional attention on alpha power, the normalized difference between attend right and attend left trials was compared to zero for young and older adults, respectively (see Figure 3). As reported by Payne et al. (2017), across the entire dichotic presentation, there were two clusters of electrodes identified in young adults for which alpha power was greater for attend right trials than for attend left trials (Figure 3, top row). One cluster was identified along the posterior midline and the second cluster consisted of right hemisphere fronto-temporal electrodes. The complementary analysis in older adults revealed one cluster for which alpha power was greater for attend right trials than for attend left trials ( $p < .05$ ). Five of these nine electrodes overlapped with the posterior cluster in young adults. As shown in the bottom row of Figure 3, the attend-right bias in alpha power was greatest during the first half of the dichotic presentation for both young and older adults. There were no clusters identified for which attend left trials had greater alpha than attend right trials in either young or older adults.

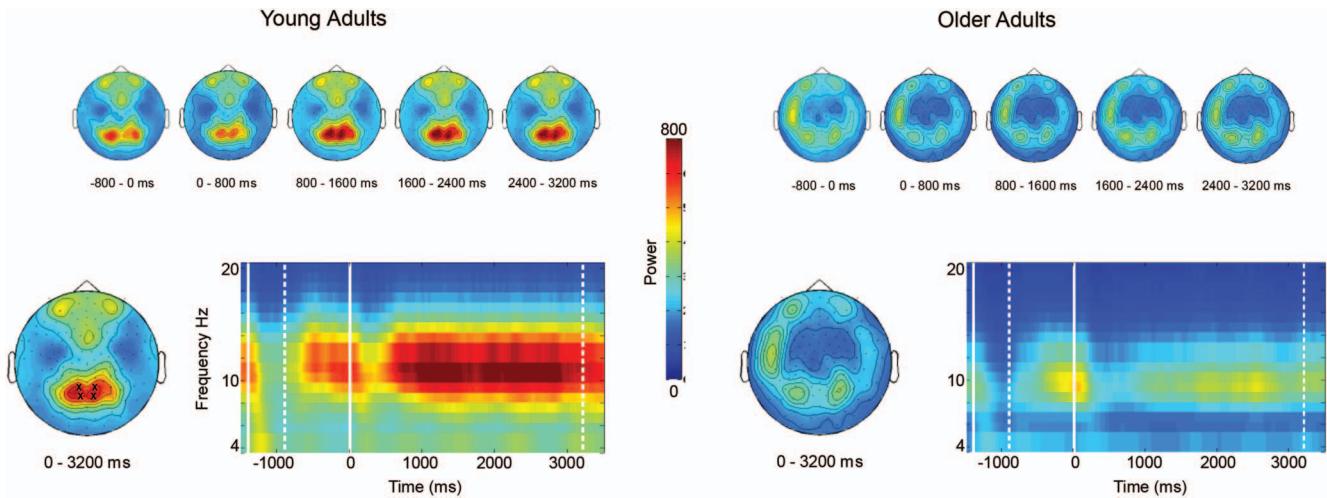
There were also no clusters identified that differed between the two directional conditions in the prestimulus epoch.

**Young versus older adults.** To establish the effect of age group on attentional modulation during dichotic presentation regardless of attended direction, alpha power was averaged across conditions and compared between young and older adults. The cluster-based, permutation test revealed a significant difference in alpha power between young and older adults during the dichotic presentation. A posterior cluster of four electrodes ( $p < .05$ ) for which alpha power was greater for young adults than older adults was identified (Figure 4, top row). Time-frequency transforms averaged across the electrode cluster confirm the striking difference in posterior activity seen within the 8–14 Hz frequency band throughout the dichotic presentation (Figure 4, bottom row). There was no significant difference found between young and older adults for the prestimulus epoch.

Given that age group differences were observed at the four posterior electrodes in the top row of Figure 4, we wished to further examine if these alpha modulations were associated with performance in the DDLT. We believe that if alpha modulation is associated with successful performance in the DDLT, we should observe overall alpha differences based on whether participants were correct or incorrect on the task. To this end, mean alpha power over this cluster of four posterior electrodes across the 3,200 ms dichotic presentation was calculated for each subject and for each of six classes of responses in this task (i.e., target hit, target miss, new CR, new FA, unattended CR, and unattended FA). Four young adults did not make any false alarms to the new probe, so we analyzed only alpha to correct and incorrect responses to the target and unattended probes. One young adult did not make any false alarms to the unattended probe and was also excluded from analysis. The results of this analysis are given in Figure 5, which



**Figure 3.** Young and older adults' lateralized alpha power during dichotic listening. Top row: Topographical plots illustrating the attend-right bias in alpha power for young and older adults across the 3,200-ms dichotic listening interval. Bottom row: Topographical plots illustrating the attend-right bias in alpha power across 800-ms bins beginning prestimulus onset and continuing through the dichotic presentation. X's mark electrodes for which the difference between attend right and attend left was greater than zero at the  $p < .05$  level; circles mark electrodes at the  $p < .01$  level. Note that positive  $t$ -values signify stronger alpha power in the attend-right condition, and negative values would signify stronger alpha power in the attend-left condition. See the online article for the color version of this figure.

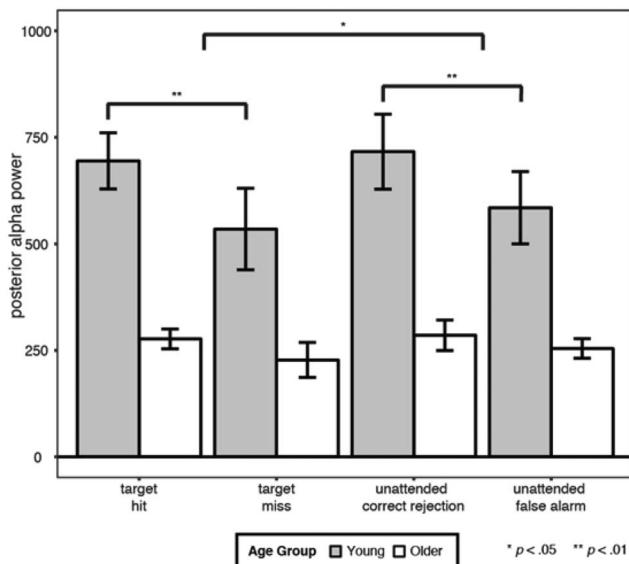


**Figure 4.** Young and older adults' alpha power during dichotic listening. Top row: Topographical plots of alpha power across 800-ms bins beginning prestimulus onset and continuing through the dichotic presentation. Bottom row: Topographical plots illustrating the average alpha power across the 3,200-ms dichotic listening interval. Electrodes marked with an X showed a significant difference between young and older adults at  $p < .05$ . The time-frequency representations for young and older adults are averaged across the cluster of parietal electrodes marked by X's in the young adult topographical plot. Stimulus onset at Time = 0 is marked by a solid white line. The dashed line at Time = 3,200 marks the stimulus offset. See the online article for the color version of this figure.

shows that alpha to young adults' correct responses is higher than incorrect responses, with no substantial difference between correct and incorrect responses for the older adults. A 2 (probe: target, unattended)  $\times$  2 (response: correct, incorrect)  $\times$  2 (age: young, older) mixed-model repeated-measures ANOVA revealed a signif-

icant Response  $\times$  Age interaction,  $F(1, 26) = 5.52$ ,  $\eta_p^2 = 0.18$ ,  $p < .05$ . Subsequent  $F$  tests revealed a significant effect of response for the young adults,  $F(1, 26) = 17.69$ ,  $\eta_p^2 = 0.40$ ,  $p < .001$ , where young adults' alpha power during dichotic presentation prior to correct responses ( $M = 705.70$ ,  $SD = 637.94$ ) exceeded that of their incorrect responses ( $M = 558.82$ ,  $SD = 532.74$ ), whereas older adults' alpha power during dichotic presentation did not significantly differ prior to correct ( $M = 281.16$ ,  $SD = 307.48$ ) versus incorrect responses ( $M = 240.93$ ,  $SD = 254.08$ ),  $F(1, 26) = 1.14$ ,  $\eta_p^2 = 0.04$ ,  $p = .29$ . ANOVA also revealed a significant effect of probe,  $F(1, 26) = 4.59$ ,  $\eta_p^2 = 0.15$ ,  $p < .05$ , indicating participants had greater alpha power during dichotic presentation on trials with an unattended probe ( $M = 451.44$ ,  $SD = 505.95$ ) compared to the target probe ( $M = 427.21$ ,  $SD = 476.33$ ).

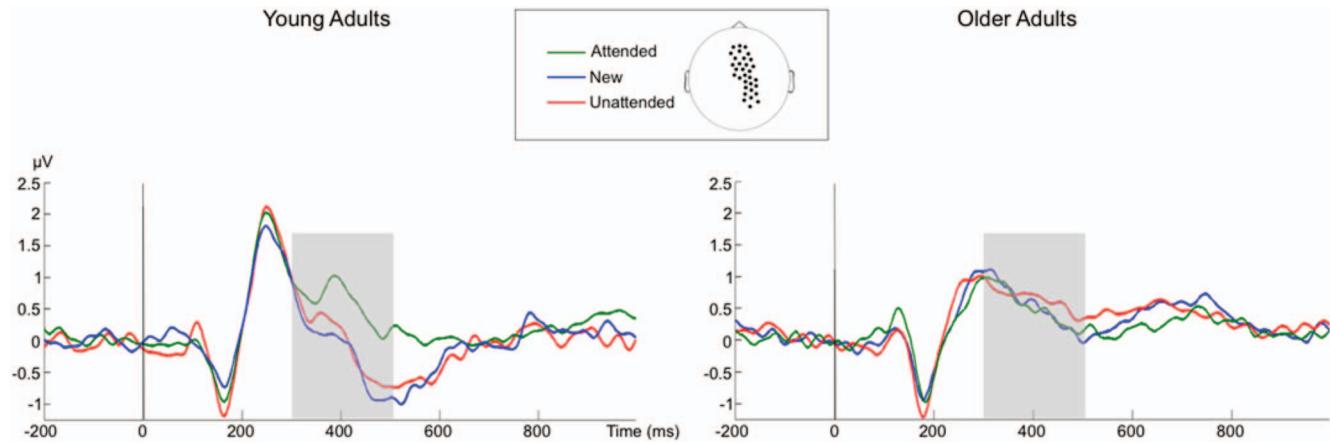
**ERPs.** Figure 6 shows the ERPs time-locked to the onset of each of the three probe types for young and older adults, respectively. For young adults, Figure 7 illustrates the midline cluster of 32 electrodes with a greater positive deflection for old (attended) words than for new (unattended and new) words during the 300 to 500 ms following word onset ( $p < .01$ ), thus replicating the old/new recognition effect. As can be seen in Figure 7B and 7C, this effect exists for both new words ( $p < .01$ ) as well as unattended words ( $p < .05$ ). For older adults, there were no significant differences found in any of the three old versus new comparisons.



**Figure 5.** Posterior alpha power during correct and incorrect responses in the directed dichotic listening task (DDLT). Significance denoted by double asterisks (\*\*) were obtained from post hoc  $F$  tests applying the Bonferroni correction that were qualified by a higher order interaction. Error bars indicate 95% confidence intervals around the mean.

## Discussion

In the DDLT, for two classes of probes, older adults' recognition performance was not reliably different from what Payne et al. (2017) had found with young adults. In particular, older and young adults differed neither in recognizing probes that had been in the attended channel, nor rejecting extralist probes that had not been

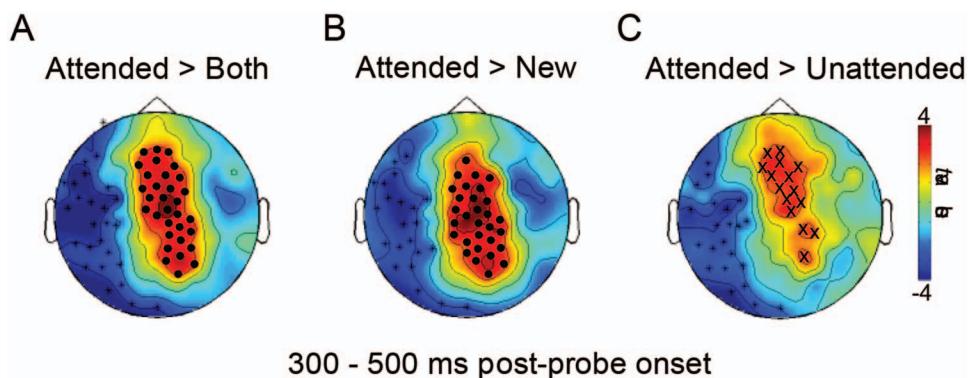


**Figure 6.** Young and older adults' event-related potentials (ERPs). Grand averaged ERPs time locked to the probe word onset for attended, unattended, and new words, drawn in green (light gray), red (dark gray), and blue (black) ink, respectively. The topographical inset depicts the cluster of electrodes included in these averages as determined by the young adult comparison between attended and both new and unattended words (as seen in **Figure 7**). The area shaded in gray marks the time from 300 to 500 ms post-probe onset during which an old/new effect was found in young adults' ERPs. See the online article for the color version of this figure.

presented in either channel. This pattern of no reliable difference between age groups differs from classic results on dichotic listening (e.g., Craik, 1965), which found age-related deficits using recall methods for assessing STM. This inconsistency is likely attributable to the current study using recognition rather than recall as the method for assessing performance. Our study did find that older adults were more likely to commit false alarms than young adults when recognition probes were words from the unattended stream. Older adults' good performance on identifying attended probes, rejecting new probes, but not for rejecting unattended probes is consistent with the notion that older adults were deficient in their inhibition of the unattended stream and thereby were less selective in their attention. An outcome of this lack of attentional control is that older adults may have been attending to both channels. This "listen to everything approach" may reflect a form

of compensation for dealing with an age-related increase in signal loss (e.g., Getzmann, 2012), inhibitory control (e.g., Hasher & Zacks, 1988), and could be related to age-related changes in listening effort (Peelle & Wingfield, 2016).

With regard to long-term memory as measured by delayed recognition, older adults had poor discriminability both for items that were attended and unattended during the DDLT. This pattern suggests not only a lack of differentiation among items encoded to long-term memory but a lack of encoding into long-term memory more generally (see also Craik & Rose, 2012). This finding is consistent with the notion that effort exerted while decoding perceptual stimuli leaves fewer processing resources available to encode that information into long-term memory (Wingfield, 2016). In comparison, young adults' delayed recognition indirectly differentiated between items that were attended and unattended dur-



**Figure 7.** A–C: Young adults' event-related potential (ERP) old/new effect. Topographical display of ERP old/new effect from 300 to 500-ms post-probe onset. A: Difference between attended and both new and unattended words. B: Difference between attended and new words. C: Difference between attended and unattended words. Electrodes within the clusters marked with a circle showed a significant difference between the two test conditions at  $p < .01$ . Those marked with an X were significantly different at  $p < .05$ . See the online article for the color version of this figure.

ing the DDLT. Young adults' below chance hit rates to unattended items indicated a suppressive role of attention during dichotic listening (cf. Thomas & Hasher, 2012).

Older adults' lack of a suppression effect may well be related to the lack of alpha power modulation that was observed in the older adults during the DDLT. Posterior alpha power was found to be greater on correct responses than incorrect responses in the DDLT, but only for young adults. Potentially, older adults' lack of alpha power differences between correct and incorrect responses may have led to older adults' accuracy decrement relative to young adults on trials in which words from the unattended channel were probed. Changes in alpha power have been presumed to reflect auditory suppression of an unattended channel in a DDLT-type paradigm (Chait et al., 2010; Choi et al., 2014; Zion Golumbic et al., 2013). It is also possible that this lack of alpha-indexed suppression is what led to the higher rate of unattended false alarms observed in older adults, as well as older adults' "listen to everything approach." It appears that older adults do not engage the processes of selective attention reflected by alpha activity to the extent that young adults do, leading to observed age-related differences in EEG alpha power (e.g., Vaden et al., 2012). It remains unclear if this reduced alpha modulation is due to an inability to control processes of sensory inhibition or a strategic shift by older adults to use alternative strategies of attentional selectivity. Further research on this topic will be needed to separate these potential causes.

One other possibility is that older adults may have had a greater cost (e.g., Kramer, Hahn, & Gopher, 1999) than young adults for switching the direction of their attention in the DDLT. As a follow-up to see if this was the case we reanalyzed the hit and false alarm data with an additional variable—whether the participant had to attend the same direction on a given trial as on one trial prior to the given trial or if the direction of the cue was switched relative to the prior trial. The results of that analysis revealed no significant effects or interactions involving the switch variable. Thereby, we find age-related differences in attention switching to be an unlikely explanatory mechanism for the current pattern of results.

Behaviorally, both young and older adults exhibited a right ear advantage in DDLT recognition performance and response latencies, with no significant differences between young and older adults in terms of laterality. Older adults' EEG alpha power also revealed a cluster of electrodes that showed an attend right bias during the DDLT. However, this posterior parietal cluster was smaller and less robust than those of the young adults in Payne et al., (2017) who showed both a posterior cluster and a frontotemporal cluster. This pattern of results suggests that although a right ear advantage certainly exists in older adults, its relationship to alpha modulation may decline with age.

Posterior alpha oscillations have been associated with auditory spatial attention when participants are presented with two simultaneous auditory streams (Ahveninen, Huang, Belliveau, Chang, & Hämäläinen, 2013; Kerlin et al., 2010; Wöstmann, Herrmann, Maess, & Obleser, 2016). A significant pattern with regard to these findings is that lateralization of parietal alpha power has been shown to indicate the direction of attention, that is, alpha power increases in the hemisphere ipsilateral to the attended side and decreases contralateral to the unattended side. In the current study, participants performing the DDLT produced greater alpha power

ipsilateral to the attending side only when attention was directed to the right ear. Although our pattern is inconsistent with the prior findings of others, we attribute this difference to a difference in stimuli we used relative to other prior studies. Kerlin et al., (2010) found neither a behavioral REA nor a right-ear bias of parietal alpha oscillations. In their design, two sentences were each attended 480 times, minimizing unique speech processing on each trial. In our study, participants attended and identified 256 individual words, presented in four-word sets, thus maximizing unique speech processing per trial. This difference is important because the right ear advantage is associated with identification of speech features (e.g., Studdert-Kennedy & Shankweiler, 1970) and, more specifically, with identification of the leading syllable (Morais & Bertelson, 1975). Given the significance of the leading syllable in speech identification, it could be surmised that early deployment of spatial attention is an important factor in directed dichotic listening.

These findings suggest a progressive top-down bias toward the representation of attended stimuli and degradation of unattended stimuli across the hierarchy of auditory processing (Lakatos et al., 2013; Mesgarani & Chang, 2012), which, our present findings suggest declines with age. Unattended speech remains represented in low-level auditory areas in and near the superior temporal gyrus, but it is no longer represented when progressing to higher-order processing regions such as the inferior frontal cortex, and anterior and inferior temporal cortex (Zion Golumbic et al., 2013). Early representation of information arriving in the unattended ear is evidenced in faster response times to a target word in the attended ear if that word follows that same word presented to the unattended ear (Dupoux, Kouider, & Mehler, 2003), or if a target word follows a semantically related word presented to the unattended ear (Bentin, Kutas, & Hillyard, 1995). More directly, the notion of early representation is corroborated by our finding of slower RTs for correct rejection of unattended words than for correct rejection of new words. Bentin et al. (1995) indirectly demonstrated the lack of representation of the unattended information during higher-order processing. These authors found that the N400, an ERP component related to semantic processing (Kutas & Hillyard, 1980), for attended words, but not unattended words, was sensitive to semantic priming. In the current study, older adults' greater rate of false alarms to the unattended channel indicate greater representation of information in the unattended ear than young adults, which suggests that the progressive top-down bias toward the representation of attended stimuli and degradation of unattended stimuli across the hierarchy of auditory processing declines with age.

The ERPs from the DDLT in this study appeared to be very similar to old/new recognition effect previously reported with young adults in short-term recognition (Crites, Delgado, Devine, & Lozano, 2000; Danker et al., 2008) and delayed recognition (Rugg & Curran, 2007). Our analysis revealed an "old/new" effect between attended targets and unattended lures. This result indicates that words from the attended stream were recognized better. Importantly, this result was true only for young adults; older adults' ERPs did not distinguish between words that were attended, unattended, or new. The timing of young adults' old/new effect, from 300 to 500 ms post stimulus onset supports the model of late selective inhibition (Lakatos et al., 2013; Zion Golumbic et al., 2013). Given the evidence for late suppression, it is likely that

some false alarms to unattended words arose from early misallocation of attention to the wrong ear (Mesgarani & Chang, 2012). It was recently reported that the direction of auditory spatial attention can be predicted by multivoxel pattern analysis of fMRI activity in the auditory cortex (Kong et al., 2014). Future work could benefit from using such a technique to identify the trials on which attention was misallocated, and whether this is a model that can be used to understand hearing operations in older adults.

The current study could be criticized for including only older adults that had clinically normal hearing, which could in turn impact its generalizability to an older adult population that has a high rate of hearing loss (Cruickshanks et al., 1998). Frequency-specific adjustments of stimulus volumes have been increasingly used in auditory research (e.g., Passow et al., 2014; Wöstmann, Herrman, Wilsch, & Obleser, 2015; Wöstmann, Schröger, & Obleser, 2015) to account for age-related decrements in hearing ability and increase the representativeness of older adult samples. That said, we believe the current results to be strong evidence of age-related changes to alpha and behavior, given they were observed in a clinically normal hearing sample that would be the least likely among older adults to show decrements on a hearing task when compared to young adults. The incidence of age-related hearing decline is known to increase processing effort (e.g., Ohlenforst et al., 2017; Peele & Wingfield, 2016) and points to an important direction for future research.

In summary, the results from the current study revealed that older adults were less likely than young adults to be selective in their attention to dichotically presented speech. Older adults' behavioral pattern of listening did not co-occur with a pattern of EEG alpha modulation that was characteristic of the young adult listeners reported by Payne et al. (2017), nor did their ERPs to short-term recognition probes distinguish among probes that were attended, unattended, or new. Older adults' delayed recognition performance did not indicate a pattern of suppression of unattended words, as was observed in the young adults. These results suggest that older adults do not engage the same cortical correlates exhibited by young adults, which may in turn explain their age-related deficit to selective auditory attention. Lastly, older adults' lack of suppression of unattended words during delayed recognition suggests that the additional cognitive load caused by selectively attending to dichotic stimuli may interfere with older adults' ability to encode speech to long-term memory.

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