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Some effects of aging on central auditory processing

Jeffrey S. Martin, MA; James F. Jerger, PhD*
School of Behavioral and Brain Sciences, The University of Texas at Dallas, Richardson, TX

Abstract—Seniors often have more difficulty understanding speech than younger adults, particularly in noisy environments. While loss in peripheral hearing sensitivity explains many of the listening problems of elderly persons, age-related declines in general cognitive skill and central auditory processing also appear to contribute. In this article, we focus primarily on the effects of age on central auditory mechanisms. To this end, we review research examining a central locus for deficits in temporal processing and summarize behavioral and event-related potential findings from our laboratory's research on the effects of aging on dichotic listening performance. Results show that age-related deficits in interhemispheric information processing may underlie some of the listening problems among seniors. We also discuss implications for clinical audiological rehabilitative efforts in this population.

Key words: aging, auditory processing, binaural interference, cognition, dichotic listening, event-related potential, gap detection, hearing aid, interhemispheric transfer, temporal processing.

INTRODUCTION

Audiologists widely accept that elderly persons have more difficulty understanding speech than their younger counterparts, particularly in noisy environments. Seniors often report that, in the presence of background noise, they may be aware that someone is talking but do not always understand what is being said. Such difficulties in speech understanding become particularly troublesome when there are multiple talkers, the rate of speech is fast, or the amount of information conveyed becomes excessive.

Certainly, many listening difficulties experienced by seniors are attributable to their presbycusic high-frequency hearing losses. Loss of peripheral hearing sensitivity, clearly, is an important factor in explaining the variation observed among seniors on different speech recognition measures [1–3]. Although degree of audibility strongly influences speech comprehension, some seniors seem to face more hurdles than would be expected based solely upon their audiometric configurations. Indeed, closer inspection of their more common complaints suggests that at least a portion of seniors' speech-understanding difficulties derive from age-related declines in cognitive abilities, changes in higher-order auditory processes, or a combination of the two.

Abbreviations: AEP = auditory evoked potential, DD = dichotic deficit, DL = dichotic listening, DSI = Dichotic Sentence Identification (test), EEG = electroencephalographic, ERP = event-related potential, LEA = left-ear advantage, LED = left-ear disadvantage, LPC = late-positive component, MCR = message-to-competition ratio, MMN = mismatch negativity, MS = morphosyntactic, PB = phonetically balanced, REA = right-ear advantage, SSI = Synthetic Sentence Identification, TL = target-left, TR = target-right, VOT = voice onset time.

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*Address all correspondence to James F. Jerger, PhD; 2612 E. Prairie Creek Drive, Richardson, TX 75080-2679; 972-883-2218. Email: jjerger@utdallas.edu

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Over the past several decades, a considerable amount of research and theoretical speculation has accumulated on age-related changes in speech perception. Much of this effort has been guided by the Report of the Working Group on Speech Understanding and Aging of the Committee on Hearing, Bioacoustics, and Biomechanics of the National Research Council [4]. Based on the Committee's findings, the three explanations of age-related declines in spoken language comprehension that have received the most attention are deficits related to—

1. Peripheral (i.e., cochlear) changes in auditory function.
2. General declines in cognitive performance.
3. Changes in more central-auditory processes [4].

In this article, our primary focus is the effect of aging on cognitive and central-auditory mechanisms, with particular emphasis on the latter. We also discuss research from our laboratory examining the effects of aging on dichotic listening performance. We then conclude with implications for clinical audiological rehabilitative efforts in this population.

COGNITIVE AGING AND SPEECH UNDERSTANDING

An ubiquitous finding in cognitive aging research is a reduction in the speed of perceptual and mental processing with advancing age [5–6]. In fact, when reaction times are used to study the "timeliness" in cognitive functions, seniors are, on average, slower than younger adults, irrespective of the tasks or the experimental procedure (Baron and Cerella, 1993, as cited in Kemmer et al. [7]). While the exact nature of age-related slowing is continuously debated, recent studies using modern electrophysiological and neuroimaging techniques to study global cognition functions, such as memory and attention, have produced valuable insights into some underlying neurobiological mechanisms (reviewed in Friedman [8] and Kok [9]).

The relative contribution of cognitive factors to seniors' speech-understanding difficulties has been controversial. Arguments against a more cognitive account are based primarily on findings that—

1. Age-related declines in cognitive functions are highly correlated with concomitant changes in peripheral sensitivity [10].
2. With the notable exception of processing speed, most attempts at correlating age-related changes in cognitive function with basic measures of speech perception have had only limited success [11].

As a result, some hearing researchers have concluded that most speech-understanding difficulties experienced by seniors are attributable to changes in peripheral hearing mechanisms rather than to age-related declines in cognitive abilities per se [12–14].

Sommers offers several reasons for the lack of significant correlations between cognitive performance and basic measures of speech perception [11]. First, the more commonly administered cognitive measures (e.g., intelligence and memory span) may not adequately reflect the speech-specific cognitive deficits contributing to seniors' speech-understanding difficulties. Second, the listening conditions and stimuli commonly used in experiments to assess speech understanding are arguably less demanding than those typically encountered in natural communication environments.

Indeed, when more complex listening and perceptual tasks are used, age-related declines in speech understanding become more substantial [15–17]. Similar findings have been observed for seniors when speech is presented in reverberant listening environments [18], interrupted noise [19], or competing speech [20]. Since many of these studies controlled for hearing sensitivity across different subject groups, these findings imply that peripheral sensitivity loss cannot account for all speech-understanding difficulties among seniors.

Difficulty in the quantification of the exact relationship between cognition and linguistic processing may be further compounded by the fact that some linguistic skills are apparently more susceptible to the effects of aging than others (reviewed in Light [21] and Kemper [22]). Although decrements in processing efficiency and working memory capacity continue to be associated with normal aging [23], language comprehension and memory for linguistic materials appear to be more well-preserved cognitive functions [24–27]. Consider, for example, the commonly reported word-finding problems experienced by seniors. Kempler and Zelinksi suggest that such difficulties do not result from disrupted knowledge structures, but rather from disrupted access to or retrieval of such knowledge [28]. A body of evidence suggesting that word knowledge remains intact throughout normal aging supports this conclusion [29–32].

Age-related declines in the production and comprehension of syntactically complex sentences may also arise largely from age-related changes in working memory [22] or in the retrieval of such information from long-term memory [30] rather than from a syntactic deficit per se. On the other hand, older adults are quite adept at using prior linguistic context to comprehend and recall information at the sentence level [20]. Indeed, older adults may be even more effective at using context than younger adults [33]. Finally, older adults appear to make excellent use of prosody to aid recognition and recall of information at both the sentence [34–36] and word [37] levels.

In summary, research confirms that seniors exhibit pronounced speech-understanding difficulties as compared with younger adults. While the effects of high-frequency sensitivity loss on speech perception in quiet are well understood, reduced speech understanding among seniors during more complex, noisy listening situations appear to involve additional factors not predictable from the audiogram. On the one hand, such findings are consistent with more cognitive models that describe an overall reduction in the speed of mental processing [38]. Seniors may invoke compensation strategies (e.g., use of context or linguistic expertise), however, to offset the effects of cognitive declines when communicating in more demanding environments. On the other hand, the possibility remains that during complex listening situations, increased listening effort resulting from age-related declines in auditory processing might compromise the allocation of cognitive resources. As Pichora-Fuller states, “it is possible that at least some of the apparent age-related differences in cognitive performance during spoken language comprehension may be secondary to auditory temporal processing deficits” [39, p. 59].

AGE-RELATED DECLINE IN AUDITORY TEMPORAL PROCESSING

Psychoacoustic Measures

A number of experimental procedures can be used to explore a listener’s sensitivity to the “timing” aspects of auditory information processing. The more common psychoacoustic approaches include gap detection measures, duration discrimination, sequential interference (i.e., temporal masking), temporal ordering, and manipulation of selective temporal aspects of speech features (e.g., time-compression). Fitzgibbons and Gordon-Salant more completely describe many of these procedures [15].

Historically, a listener’s ability to recognize the presence of brief temporal intervals has been evaluated with gap-detection procedures. For individuals with hearing loss, a common finding is the elevation of gap-detection thresholds [40–44]. Thus, decrements in peripheral sensitivity would likely contribute to the temporal processing difficulties observed among individuals with presbycusis. Indeed, most psychophysical models relate declines in temporal resolution ability, as measured by gap-detection procedures, to limitations in sensory processing [15]. However, elevated gap-detection thresholds were also observed when seniors had clinically normal hearing sensitivity or when their hearing status was matched to younger listeners [18,45–48]. For example, Schneider and Hamstra examined whether varying the durations of the two stimuli or “markers” preceding and following the gap affected the gap-detection abilities of young adults with normal hearing and older adults with relatively normal hearing at the test frequency [49]. The study also controlled for the effects of “off-frequency listening” which might influence detection of the gap. Findings revealed gap thresholds in older adults that were significantly elevated for shorter marker durations ($\leq$ 200 ms) but converged with those from younger adults at longer marker durations. These findings “confirm previous reports of gap-detection thresholds, suggesting that age-related changes in temporal acuity may occur independently of age-related changes in audiometric acuity” [49, p. 375].

Hearing loss certainly influences gap-detection performance among seniors [40–41]. While declines in performance likely involve changes in cochlear mechanisms [50–51], other researchers have proposed the involvement of central auditory processes [49,52]. In Schneider and Hamstra’s 1999 study, age-related declines in gap-detection performance were most robust for shorter marker durations. They relate such decrements to possible prolonged neural adaptation in older individuals [49]. Recent findings on the neural correlates of gap detection in the single-unit neural responses from the mammalian central auditory system (e.g., inferior colliculus) are consistent with this view [53–55].

In summary, evidence is increasing that other aspects of central auditory aging, independent of peripheral hearing sensitivity, underlie some of the temporal processing deficits observed in basic gap-detection measures. Investigators examining duration-discrimination abilities between younger and older adults with simple noise and tonal stimuli have reached a similar conclusion [56–59].

While the ability to discern silent intervals and durations that signal phonetic contrasts in normal speech is linguistically important [60], the degree to which smaller, yet significant, age effects obtained on psychoacoustic measures (i.e., gap detection) influence speech understanding in seniors is controversial. Indeed, considerable discussion surrounds the topic. Some reports indicate a relationship between performances on psychometric procedures (e.g., gap detection) and various speech perception tasks [18,42,44,61–62], whereas other studies have not found a strong relationship [48,52,63–67]. Additional concern surrounds the more commonly used stimulus materials, typically tones or noises delivered to a single ear via headphones. Decades of research in cerebral laterality would suggest that linguistic (or perceived linguistic) and nonlinguistic materials are processed in fundamentally different manners and furthermore likely invoke anatomically and functionally distinct brain areas (reviewed in Hellige [68]).

In any event, more recent studies have also indicated that older listeners have more difficulty discriminating fine acoustic cues and extracting the temporal information relevant for identifying speech contrasts [69]. Studies incorporating varying time-compression algorithms in single words, phrases, and sentences have revealed age-related difficulties in processing the brief acoustic cues inherent in rapid speech [70–72]. Of perhaps even greater importance to the current discussion is that the age-related deficits in temporal processing observed in these studies cannot be explained by peripheral hearing loss.

Electrophysiological Measures

Electrophysiological studies also support the theory that a central locus underlies age-related declines in auditory temporal processing. Most have focused on the preattentive and sensory encoding aspects of auditory temporal processing, as revealed by the mismatch negativity (MMN) and P1-N1-P2 complex of the late auditory evoked potential (AEP). The MMN is believed to reflect automatic detection of stimulus change in the auditory system (e.g., duration and frequency) and to be generated by sources in or near the primary auditory cortex [73–74]. The N1 component of the N1-P2 complex is believed to reflect synchronous neural activity from thalamic-cortical structures within the central nervous system and to be controlled by more physical and temporal aspects of stimulus change [75]. Both measures (MMN and N1) appear well suited for the examination of temporal acuity in sensory processing by the central auditory system.

While the literature is replete with studies examining the MMN elicited by various temporal deviations in auditory stimulus parameters, relatively few have examined temporal auditory processing and the effects of age on the MMN. Of those that have, temporal resolution has most often been assessed by the MMN elicited by either duration or frequency changes. In a recent review of the topic, Pekkonen found that most studies showed a reduction in seniors' MMN for duration deviance but not consistently for frequency deviance [76]. In light of these findings, Pekkonen concluded that seniors showed an "age-related impairment in the automatic discrimination of duration deviance . . . and that the MMN generators activated by duration and frequency deviation and environmental sounds have different age-related patterns of sensitivity" [76, p. 219].

Bertoli et al. also recently reported a reduction in seniors' MMN to duration deviance [77]. They compared behavioral performance on a relatively simple psychoacoustic gap-detection procedure between younger and older adults with normal hearing. MMN responses were obtained with deviant stimuli of varying gap durations while participants read a text. Results showed no significant differences between groups on the psychoacoustic task, but seniors required longer gap durations to elicit an MMN. Moreover, these responses were reduced in amplitude and prolonged in latency. Although larger MMN gap thresholds for the group of seniors contrast with the psychoacoustic data collected from these same individuals, the results nonetheless suggest that poorer performance by some seniors on more complex psychoacoustic measures of temporal processing arise, to some extent, from deficits at the automatic preattentive level. The degree to which attention modulates the MMN, however, is an ongoing debate.

A recent study by Tremblay et al. [78] extends previous reports suggesting that age-related difficulties in processing time-varying acoustic cues [52,79] arise from auditory cortex temporal-resolution dysfunctions [80]. The N1 response latency of both far-field [81] and near-field [82] neural responses can reflect changes in voice onset time (VOT), a temporal cue distinguishing the perception of different phonemic contrasts (e.g., /ba/ to /pa/). Based on these findings, Tremblay et al. examined the effects of age and hearing loss on perception and neural representation of VOT [78]. Three groups of listeners were included:

1. Young adults with normal hearing.
2. Seniors with normal hearing.
3. Seniors with presbycusis.

All listeners participated in a same-different task involving the recognition of different speech tokens along the /ba/ to /pa/ continuum, varying from 0 to 60 ms VOT in 10 ms increments. AEPs (N1-P2) were obtained with the same stimuli while listeners watched a closed-captioned movie. Behaviorally, both older adult groups, as compared with younger adults, had difficulty discriminating the 10 ms VOT contrasts. Electrophysiologically, both older groups showed prolonged N1 and P2 latencies with increased VOT durations. While the exact neural mechanisms underlying VOT perception are still unknown, Tremblay et al.'s results provide further evidence that some speech-understanding difficulties among seniors may arise from changes in the temporal response properties of the aging central auditory system [78].

AGING AND BILATERAL ASYMMETRY

Additional evidence of age-related changes in central auditory processing comes from dichotic listening (DL) studies. In this experimental approach, listeners simultaneously receive competing auditory signals, one or more being presented to each ear. When linguistic materials such as syllables or words are used, a majority of individuals tend to report more accurately the information presented to their right ear as compared with their left ear (i.e., a "right-ear advantage" [REA]). Conversely, when nonlinguistic materials are used, such as environmental noises or complex tone bursts differing in their fundamental frequencies, information presented to the left ear is more accurately reported than that presented to the right ear (i.e., a "left-ear advantage" [LEA]). Asymmetry in behavioral performance is believed to reflect underlying hemispheric biases in processing different aspects of auditory information [68].

The exact neural mechanisms contributing to interaural asymmetry, however, remain controversial. Historically, the two general models explaining ear advantages during DL have been—

1. A structural model emphasizing more "automatic" or "bottom-up" processing biases.
2. An attentional model implicating more "controlled" or "top-down" factors [83].

The "classic" structural model, originally proposed by Kimura [84], posits that the REA arises from static asymmetries along the neural pathways connecting the auditory periphery and more central auditory structures at the cortical level. The attentional model, originally proposed by Kinsbourne [85], argues that aural asymmetries arise from a cognitive or attentional bias toward the hemispace contralateral to the engaged cerebral hemisphere (Jerger and Martin provide a general description of DL models [86]).

Neither model uniquely explains the aural asymmetries observed. Although many theoretical posits underlying the structural model have been supported, the influence of higher-order cognitive processes, such as directing attention, can substantially alter the experimental outcome (reviewed in Hugdahl [87]). Despite continued debate over the exact underlying neural mechanisms, DL is generally accepted to stress both intrahemispheric processing and interhemispheric cooperation. A considerable amount of research has implicated an increased role of interhemispheric interactions under attentionally demanding listening conditions [88–89]. Thus, we might question whether age-related deficits in information processing between the hemispheres are a factor in at least some listening problems faced by seniors.

Left-Ear Disadvantage with Advancing Age

Early DL studies produced conflicting results as to whether the REA, or more appropriately, the "left-ear disadvantage" (LED) changed with advancing age. Some reports showed no effect of age [90–92], whereas others noted increased LED among elderly listeners [93–95].

To further explore possible effects of age and hearing loss on ear advantage, Jerger and Jordan compared performances between a group of young and older adults on a cued-listening task [96]. All young adults had normal hearing, whereas seniors showed varying degrees of sensorineural hearing loss consistent with presbycusis. In their dichotic task, participants were instructed to listen to a short narrative and manually indicate (i.e., press a response button) when they heard the target stimulus, the personal pronoun "I." Auditory stimuli were presented from three loudspeakers, two positioned on either side of the participant and a third positioned above and slightly behind the participant's head. Listeners were asked to attend only to the narrative presented from a precued side (i.e., the right or left loudspeaker) and to ignore a competing message from the other side. The presentation intensity of the continuous discourse was adjusted to each participant's comfortable listening level. To manipulate the difficulty of the task, Jerger and Jordan presented multitalker babble from the loudspeaker positioned above the participant. The intensity of the babble was varied to produce message-to-competition ratios (MCRs) of 0, –5,

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–10, and –15 dB. Jerger and Jordan provide a more complete description of experimental methods [96].

Figure 1 shows the differences between accuracy scores as a function of attended side and MCR. In both groups, the positive deflection in the function from baseline is consistent with the LED for processing linguistic materials. For young adults, there was a slight (yet significant) advantage in performance for right-sided targets compared with left-sided targets. The difference, however, was relatively constant across different MCRs. For the group of seniors, a different pattern emerged. Here, the LED was overall more substantial and increased as the listening environment became more unfavorable (i.e., as the MCR decreased). Overall, these results agreed with previous reports showing an effect of age on the degree of aural asymmetry.

One might ask whether audiometric asymmetries contributed to the increased LED observed in the group of seniors. Several lines of evidence argue against such a hypothesis. First, differences in hearing sensitivity between both ears were minimal. In fact, hearing thresholds were slightly better for the left ear. Second, average differences between ears on other measures of speech perception, like recognition of phonetically balanced (PB) words and Synthetic Sentence Identification (SSI) scores [97] were also negligible.

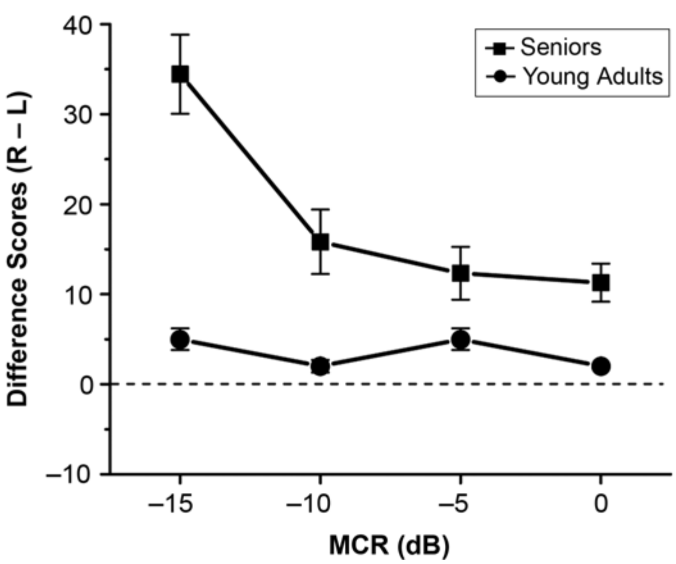

Figure 1.
Mean difference between right-sided and left-sided (R – L) accuracy scores as a function of message-to-competition ratio (MCR) on cued-listening task for young adults (n = 19) and seniors (n = 28). Error bars denote standard error of mean. *Adapted from:* Jerger J, Jordan C. Age-related asymmetry on a cued-listening task. Ear Hear. 1992;13(4): 272–77.

Contribution of Structural-Auditory and Cognitive-Attentional Factors to LED in Elderly Listeners

Hearing researchers are particularly interested in the degree to which “ear deficits” are attributable to age-related structural changes within the central auditory system. The most common approach in differentiating structural from cognitive factors is to control for the attentional component. Much of the early DL work followed Broadbent’s general divided-attention mode [98]. Listeners were instructed to repeat in any order they chose everything heard in both ears (i.e., divided attention). Out of concern that this mode fails to control for a number of bias sources, such as spatial attention, researchers have proposed more focused-attention procedures, known as directed attention (reviewed in Voyer and Flight [99]). In directed-attention procedures, listeners are instructed to attend to the stimulus in only one ear. A comparison of listeners’ responses during both divided- and directed-attention listening modes can be used to assess the influence of spatial attentional factors. Since certain aspects of attention change with aging [9], might seniors’ increased LEDs reflect further declines in cognitive abilities?

To examine the effects of instructional set and degree of hearing loss on interaural asymmetry, Jerger et al. retrospectively analyzed DL performance of 356 listeners aged 9 to 91 with either bilateral normal hearing or bilateral sensorineural hearing loss [100]. They compared findings from routine audiological procedures, including pure-tone hearing sensitivity, basic speech perception measures (e.g., PB words and SSI), and a modified version of the Dichotic Sentence Identification (DSI) test [101].

For the DSI test, participants were instructed to listen to dichotically paired sentences in the divided-attention and directed-attention listening modes. In the divided mode, listeners identified both sentences heard in each trial. In the directed mode, listeners indicated only the sentence heard in a single ear, which was precued prior to a block of trials. Jerger et al. provide a more complete description of DSI methods and scoring [100].

Figure 2 shows the distribution of ear advantage across different age groups and for both listening modes. Rather than displayed to show the differences in performance between ears (i.e., right minus left), the data have been plotted to simply show the percentage of individuals in each age group that exhibited an ear advantage. This approach minimizes to some degree the problems associated with

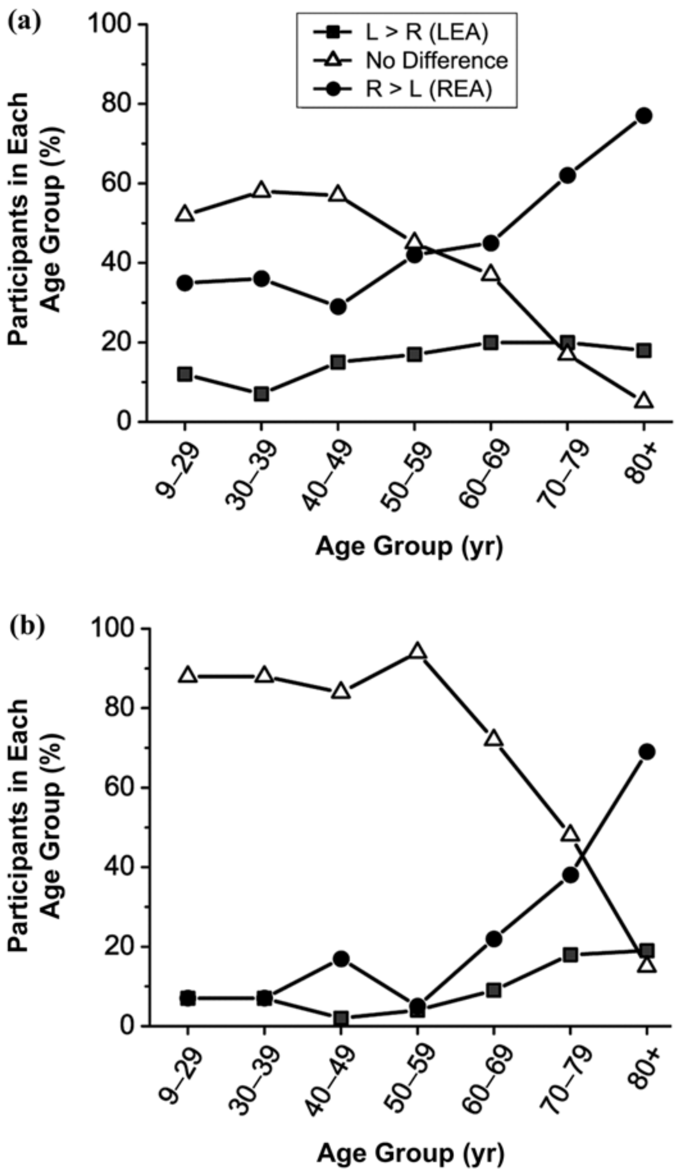

Figure 2.
Distribution of right (R) and left (L) ear advantages (REA and LEA) (n = 356) as a function of age in **(a)** divided-attention and **(b)** directed-attention modes. *Adapted from:* Jerger J, Chmiel R, Allen J, Wilson A. Effects of age and gender on dichotic sentence identification. Ear Hear. 1994;15(4):274–86.

ceiling effects (e.g., 100% performance for both ears in both the divided-attention and directed-attention modes). Three outcomes were possible irrespective of the actual numerical scores:

1. An advantage of the right ear (i.e., REA).
2. An advantage of the left ear (i.e., LEA).
3. No ear advantage (i.e., equal performance).

The divided-attention mode, shown in **Figure 2(a)**, evidenced several findings. First, the number of listeners that failed to show any ear advantage decreased with advancing age. Second, fewer listeners overall exhibited an LEA. Moreover, the proportion remained fairly constant across the different age groups. Third, the number of individuals showing an REA-LED steadily increased with age. In the directed-attention mode, shown in **Figure 2(b)**, the ear advantages previously observed for the younger groups virtually disappeared. Beginning at about the age of 60, however, the number of individuals showing an REA-LED increased substantially while the proportion showing an LEA remained fairly constant.

The data in **Figure 2** clearly illustrate the influence of attention on DL performance. Interestingly, the greatest changes in performance between listening modes occurred for younger listeners. While the directed-attention mode reduced the overall number of REA-LED cases across the age groups, a considerable percentage of older adults nonetheless showed an REA-LED.

Figure 3 shows a more detailed view of the actual performances from the four oldest age groups. Overall performance was better in the directed-attention mode than in the divided-attention mode. This better performance in the directed-attention mode irrespective of age group is likely due to the reduced attentional demands characteristic of this listening mode. The magnitude of the REA-LED across age groups and listening modes, however, remained similar. Since the purpose of the directed-attention procedure is to minimize the cognitive or attentional demands associated with the DL task, what explains the persistent REA-LED for older listeners? The results summarized in the next section support an explanation based on a structural-auditory pathway effect rather than on cognitive changes.

Age-Related Declines in Interhemispheric Transfer of Auditory Information

To examine a possible neurophysiological basis for the large, age-related aural asymmetries previously observed [96,100], Jerger and colleagues carried out a subsequent study that incorporated both behavioral and auditory event-related potential (ERP) measures [102]. Experimental procedures were carried out with young adults with normal hearing, seniors with presbycusis, and seniors with presbycusis and previously documented, substantial interaural asymmetries (dichotic deficits [DDs]).

Jerger et al. directly compared performances of the two senior groups to examine whether individuals with

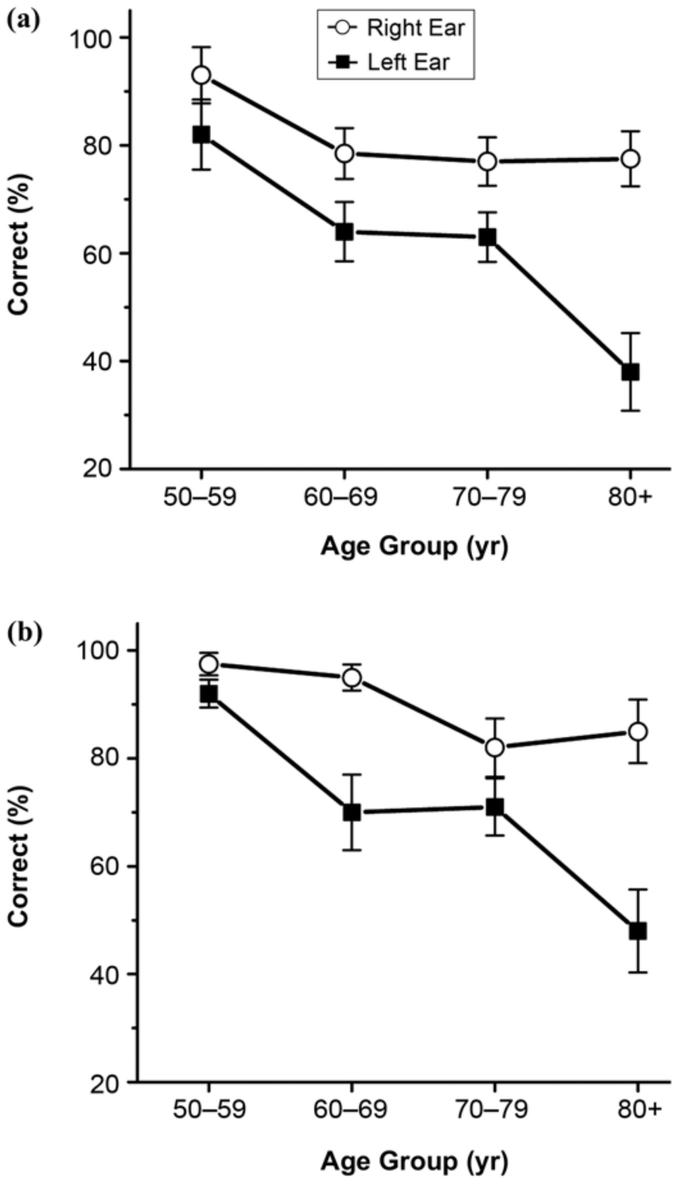

Figure 3.
Mean percent correct scores with standard error of mean for right and left ears for seniors (n = 78) aged 50–91 in **(a)** divided-attention and **(b)** directed-attention modes. *Adapted from:* Jerger J, Chmiel R, Allen J, Wilson A. Effects of age and gender on dichotic sentence identification. Ear Hear. 1994;15(4):274–86.

pronounced DDs represent an extreme form of the general aging population [102]. To rule out the possibility that distortion from peripheral hearing loss explained findings, they included a fourth group of normal-hearing young adults for whom auditory input was severely degraded electronically.

Behavioral and ERP data were collected from all listeners during two DL tasks, one involving a linguistic target feature and the other, a nonlinguistic target feature. Both types of target features were included because of the substantial literature demonstrating differences in hemispheric biases for processing verbal and nonverbal aspects of language [68]. If the pronounced LEDs observed among some seniors during linguistic processing could be reversed for nonlinguistic processing (i.e., a right ear disadvantage), it might further substantiate the role of reduced interhemispheric connectivity in some speech-understanding difficulties.

In both listening tasks, pairs of monosyllabic words were presented in the dichotic mode by a male speaker via two loudspeakers positioned on either side of the listener's head. Stimuli were presented in the basic "oddball" paradigm, in which target trials occurred on a relatively smaller percentage of the total number of trials (e.g., 30% in total, 15% to the left side, 15% to the right side). Targets were presented pseudorandomly among more frequently occurring nontarget trials. Stimuli were presented at a comfortable loudness level, but the interaural intensity ratio in the loudspeaker settings remained the same.

For the linguistic task, target trials consisted of any random word paired with a word from a predefined phonemic category (i.e., words that rhymed with "book"). For the nonlinguistic task, target trials consisted of a random word paired with any word spoken by a female speaker (i.e., a spectral feature). Listeners responded to target and nontarget stimuli via two response buttons, labeled *yes* and *no*, positioned in front of them. Thus, both accuracy and reaction times were collected. While listeners engaged in each listening task, brain activity was concurrently recorded from 22 gold-cup surface electrodes affixed to the scalp according to the International 10-20 system. Individual sweeps of electroencephalographic (EEG) activity, time-locked to the onset of the stimuli, were recorded via the Neuroscan acquisition software (Compumedics, El Paso, TX) and stored for later analysis. Individual epochs containing ocular artifact were excluded from the averaged target-right (TR) and target-left (TL) waveforms obtained from both dichotic tasks. Jerger et al. provide a complete description of behavioral and electrophysiological methods and materials [102].

Figure 4 compares the average accuracy scores and reaction times across the four groups of listeners for right-sided and left-sided targets in the verbal task.

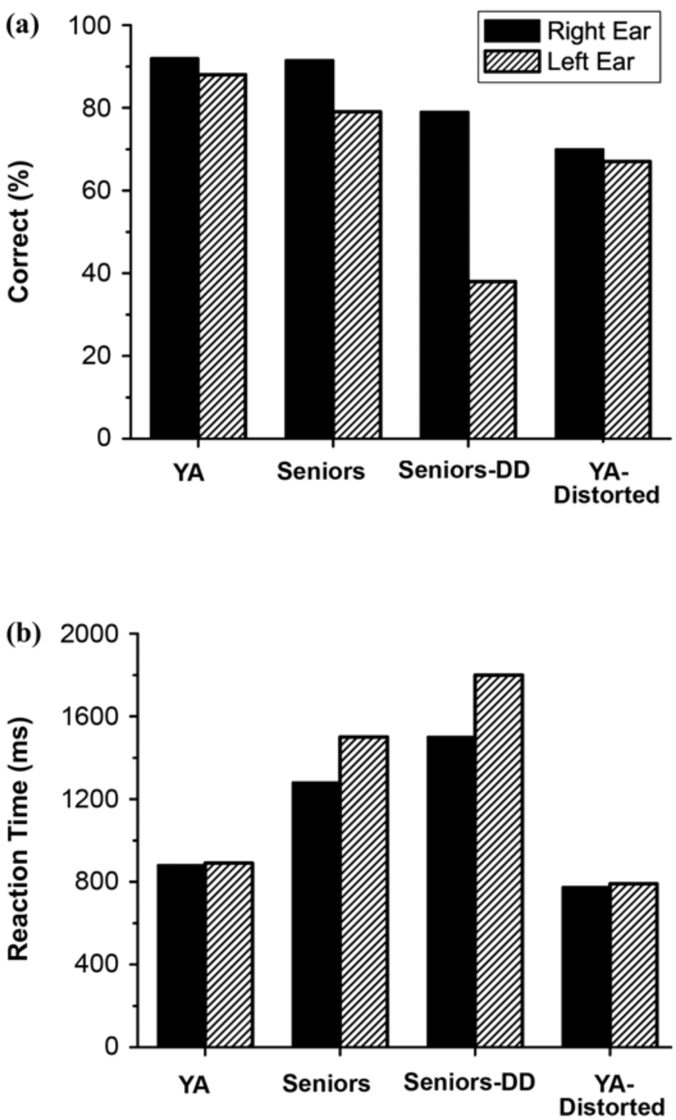

Figure 4.
Comparison of **(a)** mean accuracy scores and **(b)** reaction times for right-sided and left-sided targets in verbal task among four listener groups: young adults (YA), seniors with presbycusis (Seniors), seniors with presbycusis and known dichotic deficits (Seniors-DD) and YA with simulated peripheral distortion (YA-Distorted). *Adapted from:* Jerger J, Alford B, Lew H, Rivera V, Chmiel R. Dichotic listening, event-related potentials, and interhemispheric transfer in the elderly. Ear Hear. 1995;16(5):482–98.

Several findings are apparent in the accuracy data shown in **Figure 4(a)**. First, all groups had better overall performance when targets were presented from the right side compared with the left side. While the REA-LED was larger for both groups of seniors compared with the young adults, it was more pronounced for the seniors with marked DDs. Second, although overall performance decreased for the young-adult group in which the speech signal had been severely distorted, the magnitude of this group's REA did not change.

As shown in **Figure 4(b)**, reaction time data for the verbal task revealed similar results. First, collapsed across target side, both senior groups had longer overall response times compared with the young-adult groups. Second, both senior groups displayed a difference in reaction times between right-sided and left-sided targets. Responses in the TR condition were earlier (i.e., an LED). Finally, artificially degraded auditory input did not affect response latencies for young adults.

Figure 5 compares the differences between right-sided and left-sided targets as reflected by common auditory ERP measures of peak amplitude and latency. Data are shown for the young adult and senior groups on the verbal and nonverbal dichotic tasks. Picton offers a complete description of individual ERP components [103]. In brief, earlier waveform components, such as the MMN or auditory N1 component, are believed to reflect more preattentive, sensory-encoding aspects of stimulus change, whereas later occurring components, such as the late-positive component (LPC), reflect more cognitive aspects of auditory processing. Thus, to compare both behavioral and electrophysiological measures of performance, the data in **Figure 5** represent the LPC. Amplitude and latency values from individual participant waveforms were taken from an electrode (P3) that most represented the maximum LPC amplitude across the 30-electrode array.

For the LPC amplitudes shown in **Figure 5(a)**, a positive deflection from baseline indicates a larger response to targets presented on the right side compared with the left side. For the verbal task, Young Adults showed only a slightly stronger response (i.e., REA) to right-sided targets. The ear difference increased for both groups of older listeners but was particularly large for the Seniors-DD group. For the nonverbal task, minimal ear differences were observed for both Young Adults and Seniors. The Seniors-DD group, however, showed a considerably larger ear difference favoring left-sided targets.

LPC latency data in **Figure 5(b)** show a similar pattern. Here, negative values indicate an earlier response to targets presented on the right side compared with the left side. For the verbal task, Young Adults again showed only a slightly earlier response (i.e., REA) to right-sided targets. The ear difference increased for both groups of older listeners but was again larger for the Seniors-DD

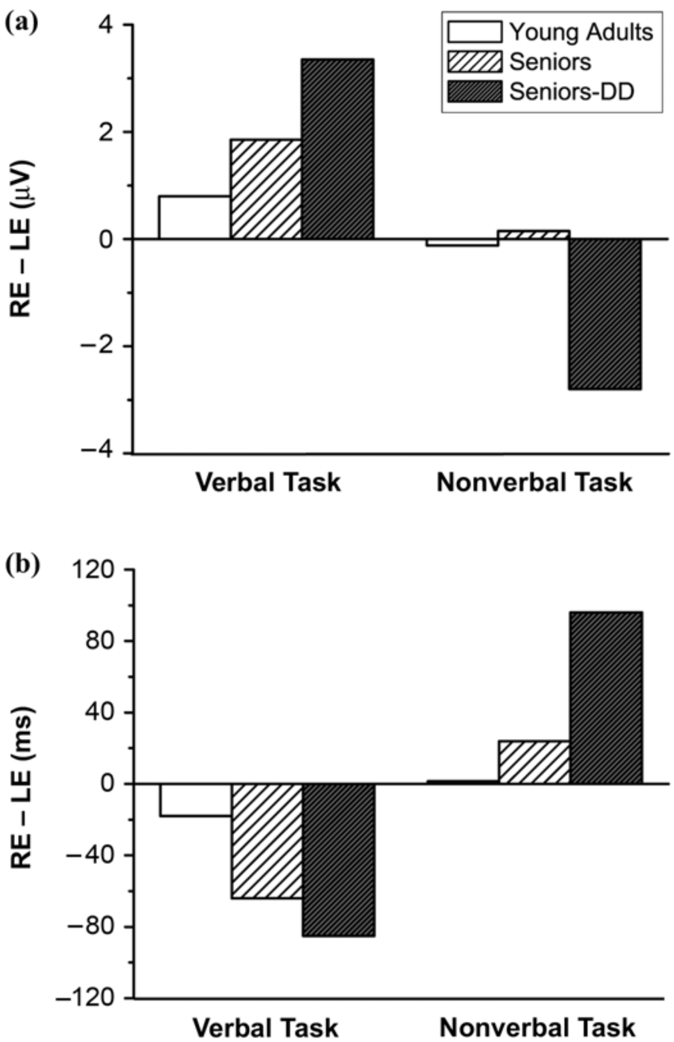

Figure 5.
Average late-positive component **(a)** amplitudes and **(b)** latencies plotted as right ear (RE) and left ear (LE) differences for both verbal and nonverbal tasks in young adults, seniors, and seniors with substantial dichotic deficits (Seniors-DD). *Adapted from:* Jerger J, Alford B, Lew H, Rivera V, Chmiel R. Dichotic listening, event-related potentials, and interhemispheric transfer in the elderly. Ear Hear. 1995;16(5):482–98.

group. For the nonverbal task, the Seniors-DD group showed a considerable ear difference favoring left-side targets.

The fact that reaction times in **Figure 4(b)** were overall longer for both senior groups was not unexpected. This finding agrees with numerous reports illustrating a general slowing in perceptual processing with advancing age [38]. Indeed, if we compare actual reaction times with LPC latencies on the verbal task, we could reasonably conclude that much of the observed differences in behavioral responses was compounded by general declines in motor abilities. In any event, both groups of seniors, compared with young adults, showed increased LED on the verbal task. Interestingly, the seniors displayed the opposite pattern of results (i.e., a right-ear disadvantage) for accuracy and reaction time on the nonverbal task (not shown). This reversed interaural asymmetry was also confirmed by the pattern of electrophysiological responses (**Figure 5**).

The overall pattern of results suggests a unique change in central auditory processing among some seniors. The most parsimonious explanation for the reversal in interaural asymmetry between listening tasks is a change in the efficiency of interhemispheric transfer of auditory information across the corpus callosum rather than a change in one or both afferent auditory pathways per se.

This conclusion finds additional support from studies implicating the role of the corpus callosum in mediation of verbal responses from left-ear inputs [104–106] and documented age-related changes in the corpus callosum [107–108].

Finally, one could argue that hearing loss combines with normal callosal delay in some multiplicative manner, exacerbating an otherwise small interaural difference. This hypothesis, however, was not supported by results from the group of normal-hearing young adults who listened to severely degraded auditory inputs. Ear differences were overall absent for this group.

Ecological Validity and Effect of Age on Interaural Asymmetry

The bulk of ERP research on the effect of age on interaural asymmetry has used relatively simple stimuli, typically pure tones, nonsense syllables, or monosyllabic words. While these studies have yielded important insights into the neural mechanisms underlying central auditory processing, such stimuli are seldom experienced in isolation in the real world. In a search for greater ecological validity, Jerger et al. examined young adults' and seniors' DL performances with a task that better represented the natural listening environment [109–110]. Seniors showed mild to moderate presbycusic hearing sensitivity loss with similar audiometric configurations for the right and left ears.

Listeners were instructed to listen to a short narrative from two classic children's fairy tales. Throughout the story, some words were replaced by inappropriate or anomalous words (i.e., morphosyntactic [MS] anomalies). Auditory stimuli were presented at a comfortable loudness level from two loudspeakers positioned to the right and left sides of each participant. Participants were asked to attend only to the narrative presented from one side and to disregard a competing message from the other side. As in a previous study [96], competition consisted of the same narrative delayed in time with respect to the information presented in the attended ear (i.e., a different part of the story). The listener's task was to silently count the MS anomalies heard in the attended ear. The complete procedure was carried out over several attend-right (i.e., TR) and attend-left (i.e., TL) blocks, with the direction of the first block counterbalanced across different listeners.

EEG activity was simultaneously recorded from 30 silver-silver chloride electrodes mounted in an elastic cap (Compumedics, El Paso, TX) and affixed to the scalp according to a modification of the International 10-20 system. Individual sweeps of EEG activity, time-locked to the onsets of the anomalous words, were collected via the Neuroscan acquisition software (Compumedics, El Paso, TX) and stored for later analysis. Individual epochs containing ocular artifact were excluded from the averaged waveforms corresponding to targets in the TR and TL conditions. Jerger et al. provide a complete description of behavioral and electrophysiological methods and materials [109–110].

Figure 6 shows grand-averaged ERP waveforms elicited by the MS anomalies to both TR and TL stimulation and for both younger (**Figure 6(a)**) and older (**Figure 6(b)**) listeners. As expected, recognition of the MS anomalies produced a robust LPC in the 600 to 1,000 ms range. As seen in the figure, TR and TL grand-averaged waveforms were similar for the young adult group. For seniors, however, the LPC component between the TR and TL waveforms was clearly different. That is, young adults revealed little aural asymmetry, whereas seniors demonstrated a considerable ear difference. **Figure 6** shows means and standard errors of mean for LPC peak amplitudes (**Figure 6(c)**) and peak latencies (**Figure 6(d)**). All data were derived from the global field power transform of the entire electrode array [111]. Despite the large interaural difference for the senior group, average LPC amplitudes and latencies were nonetheless similar between groups. In fact, for the TR condition, peak latencies were even earlier for seniors.

These findings, again, confirm earlier ERP findings that elderly persons with symmetric hearing sensitivity exhibit substantial aural asymmetries during DL; specifically, a considerably weaker and later brain response occurred for information presented to the left side compared with the right side [102]. Such findings also agree with behavioral literature showing "left-ear deficits" for processing dichotic materials [96,100,112–118]. This conclusion is particularly noteworthy because it has been reached despite the different methodologies used across studies, including mode of stimulus presentation (e.g., headphones, loudspeakers), task complexity (e.g., passive listening, divided attention, directed attention), stimulus materials (e.g., syllables, words, sentences, continuous discourse), and response criteria (e.g., no response, silent counting, verbal recall, manual responses).

Effect of Age on Hemispheric Asymmetry

Up to this point, we have argued that pronounced ear disadvantages for some seniors during DL arise from an auditory structural deficit rather than an attentional-cognitive deficit per se. This does not, however, negate the possibility that age-related declines in cognitive function contribute to overall poorer DL performance. In any event, one might appropriately ask whether reduced interhemispheric connectivity affects, or possibly arises from, age-related changes in the normal hemispheric asymmetry for processing language. To this end, Greenwald and Jerger studied the hemispheric asymmetry of ERPs collected from young adults and seniors on the same directed-attention, competing-speech task involving MS anomalies described earlier [119].

Figure 7 compares area difference measurements from the grand-averaged ERP waveforms, collapsed across target side, for young adults (**Figure 7(a)**) and seniors (**Figure 7(b)**) from two lateral electrode sites that showed maximal hemispheric asymmetry. Area measures were taken at 200 ms intervals across the entire recording window. The inset square denotes the latency range corresponding to the evoked LPC. For young adults, maximal hemispheric asymmetry over the LPC interval was greatest at the frontotemporal and temporal electrode sites (FT8-FT7, T8-T7). Furthermore, as expected for a linguistic task, the direction of asymmetry clearly favored the left hemisphere. In the senior group, however, maximal hemispheric asymmetry over the LPC interval was greatest primarily at the frontal and temporoparietal electrode sites (F8-F7, TP8-TP7). The

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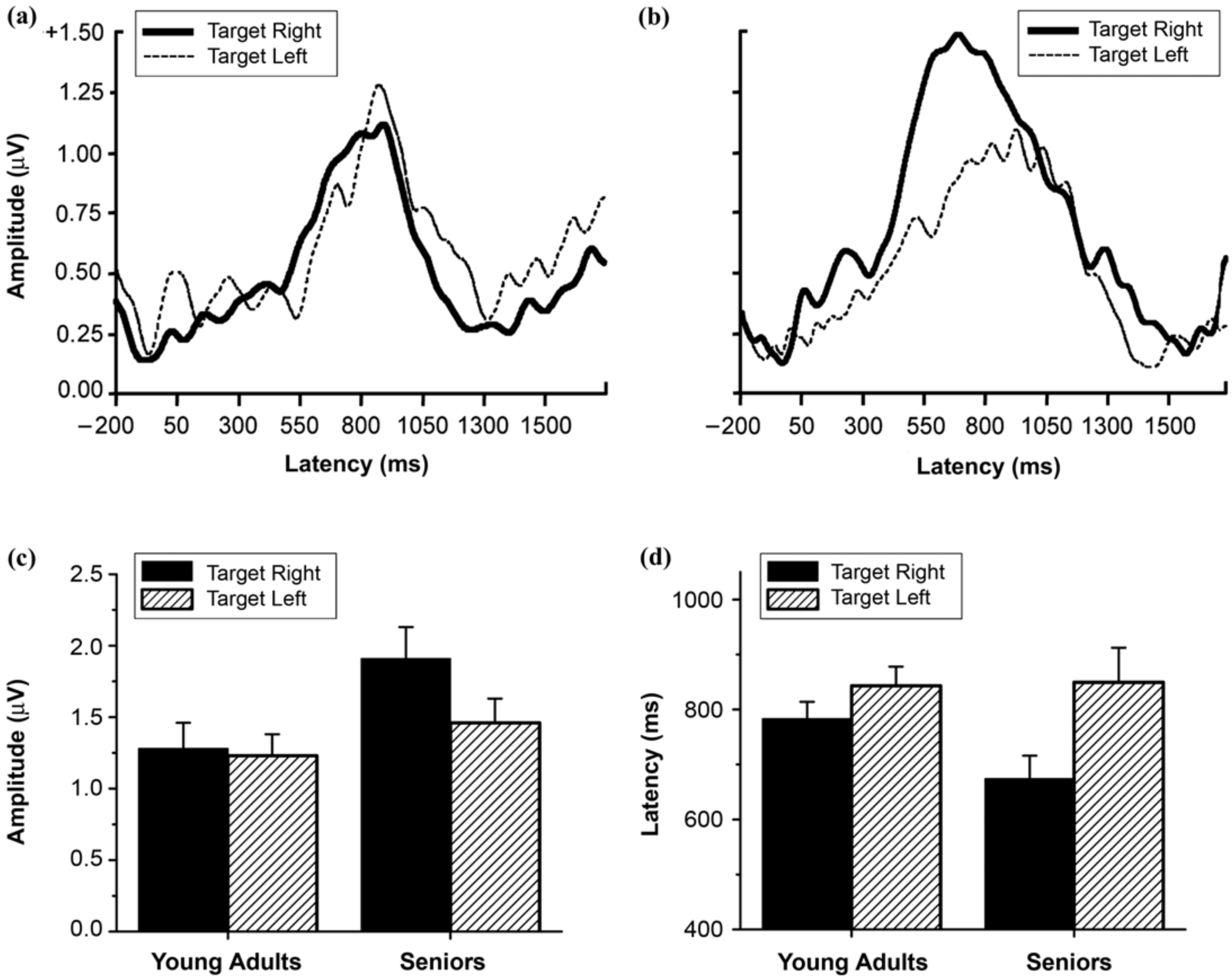

Figure 6.
Comparison between grand-averaged event-related potential waveforms of **(a)** young adults and **(b)** seniors elicited by morphosyntactic anomalies in target-right and target-left stimulation. Included are mean and standard error of mean for late-positive component peak **(c)** amplitudes and **(d)** latencies. All data are derived from global field power transform of entire electrode array. As described by Skrandies, this transform accounts for activity at all electrodes and resolves dilemma of determining appropriate electrode for measuring peak latency and peak amplitude (Skrandies W. Global field power and topographic similarity. Brain Topogr. 1990;3(1):137–41). *Adapted from*: Jerger J, Moncrieff D, Greenwald R, Wambacq I, Seipel A. Effect of age on interaural asymmetry of event related potentials in a dichotic listening task. J Am Acad Audiol. 2000;11(7):383–89.

overall degree of asymmetry was considerably reduced as compared with the young adults.

The data in **Figure 7(b)** suggest seniors have reduced hemispheric asymmetry to MS anomalies. This conclusion, however, might be the result of a cancellation of robust asymmetries occurring in opposite directions when the ERP data are collapsed across target side. **Figure 8** summarizes the results of individual subject ERP waveforms in both listener groups when TR and TL conditions were analyzed separately. The data come from the mean area differences between the two hemispheres over the latency range of 300 to 1,300 ms at the electrode site yielding maximal asymmetry seen in **Figure 7**. When the data were analyzed in this manner, the young adults' asymmetry was larger in

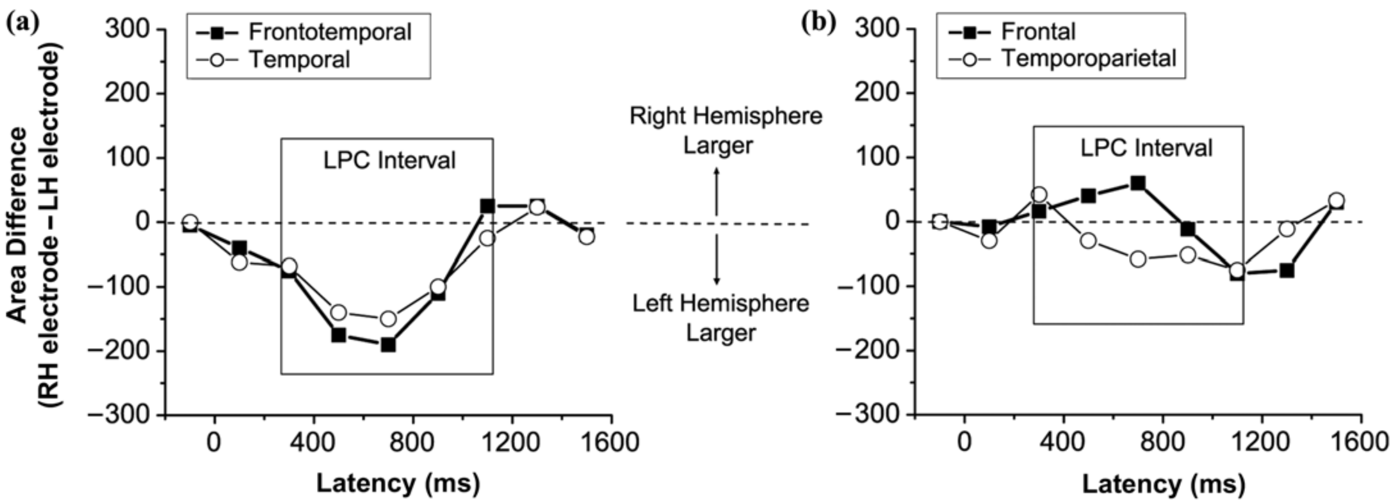

Figure 7.
Results of area analysis of right hemisphere (RH) and left hemisphere (LH). Area difference measures of hemispheric asymmetry at 200 ms intervals over latency range from –200 to 1,600 ms in **(a)** young adults and **(b)** seniors. Inset square denotes latency range corresponding to evoked late-positive component (LPC). Data based on grand-averaged event-related potential waveforms collapsed across target side. *Adapted from:* Greenwald RR, Jerger J. Aging affects hemispheric asymmetry on a competing speech task. J Am Acad Audiol. 2001;12(4):167–73.

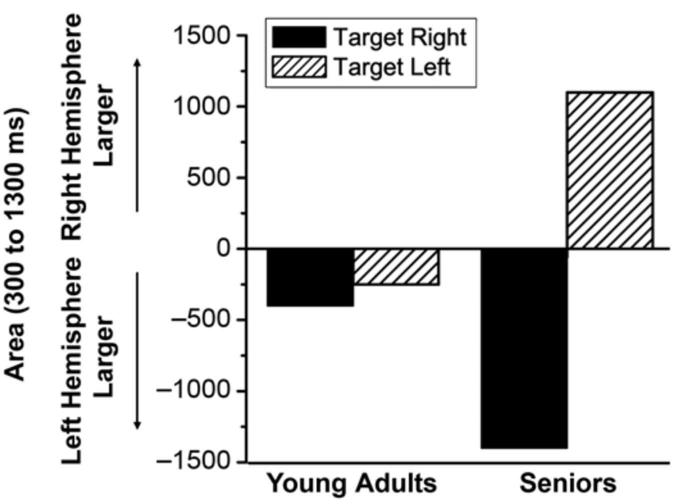

Figure 8.
Mean area difference measures (right – left) of hemispheric asymmetry over latency range from 300 to 1,300 ms in young adults and seniors. Area difference measures shown separately for target-right and target-left conditions. *Adapted from*: Greenwald RR, Jerger J. Aging affects hemispheric asymmetry on a competing speech task. J Am Acad Audiol. 2001;12(4):167–73.

the TR than the TL condition but always favored the left hemisphere. In the senior group, however, the asymmetry favored the left hemisphere in the TR condition but the right hemisphere in the TL condition.

The finding that the maximal hemispheric asymmetry occurred at more frontal sites (**Figure 7**) in elderly individuals is not unexpected and agrees with previous reports that maximal positivity in the ERP becomes more frontally distributed with advancing age [120–126]. The results in **Figure 8** are of more interest because they show an interesting pattern of hemispheric asymmetry in the senior group, one that is primarily influenced by the ear to be attended. Hymel et al. noted a similar finding among elderly individuals who listened to tones in one ear in the presence of a competing speech message [127]. They observed a left-hemispheric bias for right-ear tonal targets but a right-hemispheric bias for left-ear targets.

In summary, Greenwald and Jerger's results [119] are consistent with Jerger et al.'s previous reports that reduced efficiency of interhemispheric transfer of auditory information accompanies aging. The specific findings that topographical differences in the ERPs of older individuals reflect degraded interhemispheric connectivity have also been supported [68,128].

IMPLICATIONS FOR REHABILITATION

The observation that impairments in central auditory processing can substantially impact speech understanding in elderly persons is not new. More than 50 years ago, Gaeth wrote:

> "Evidence has been accumulated . . . which demonstrates that a phonemic regression syndrome

> exists among elderly hard-of-hearing adults. The support for this proposition is drawn from the fact that a group of adults shown to be basically similar in many aspects of their hearing loss differed significantly in the ability to hear and understand speech as measured by discrimination tests" [129, p. 131].

Gaeth further noted that, in such cases, the individual tended to report greater perceived hearing handicap than an individual of comparable age and degree of loss but without apparent central deficit. Moreover, amplification did not always alleviate the listening problem.

More recently, Chmiel and Jerger reached a similar conclusion in their evaluation of self-reported handicap scores before and after hearing aid use by seniors with and without DDs [130]. Conventional amplification addresses the issue of audibility but may not compensate for deficits in impaired temporal processing occurring within the central auditory system [78].

From an audiological perspective, whether an elderly person suspected of having a central auditory processing disorder should be fit with one versus two hearing aids is controversial. Certainly bilateral amplification has many advantages (reviewed in Holmes [131]). These advantages, however, must be weighed against the possibility of introducing more substantial processing difficulties. Specifically, contraindications to bilateral amplification have been suggested in cases of binaural interference, where binaural fittings may lead to poorer performance than monaural fittings from either ear alone [132–133]. In such cases, the auditory input from each ear may be processed quite differently, further compounding some seniors' speech-understanding difficulties in complex listening environments.

Walden and Walden's recent article illustrates the point well [118]. They compared unilaterally and bilaterally aided speech recognition in background noise in 28 older adults (50–90 years) fitted with amplification. Most listeners (23 persons) were experienced hearing aid users; all listeners had bilateral symmetric sensorineural hearing loss with no history of stroke, dementia, or other neurological disorders. Along with routine audiological procedures, listeners were tested with dichotic materials (dichotic digits) in the directed-attention mode. Several findings from their study can be summarized. First, a majority of listeners (82%) showed better speech recognition with unilateral rather than bilateral amplification; this effect increased with background noise level. Second, 78 percent achieved better performance with the right ear aided than with the left ear aided. Interestingly, the direction of the disadvantage (i.e., LED) is consistent with findings from other dichotic studies in elderly persons. Although dichotic performance in this study did not correlate significantly with the speech-in-noise performance of the better ear, the results nonetheless suggest that, even when auditory peripheral sensitivity is symmetric, more central auditory factors underlying success with amplification may be involved.

Assistive listening devices are another amplification resource for elderly persons (reviewed in Lesner [134]). Such devices can be used alone or as an adjunct to conventional hearing aids. They typically employ either infrared or frequency-modulated electromagnetic carrier waves. In essence, the transmitting microphone is mobile and can be moved closer to the talker(s) when the listening environment becomes more hostile. This leads to an improved signal-to-background noise ratio at the listener's ear. Many elderly persons with hearing loss have found that this improvement provides more assistance than conventional hearing aid amplification in difficult listening situations. For children and older adults suspected of having centrally based auditory impairments, assistive listening devices are a key factor in the prognosis for audiological rehabilitation [135–136]. The disadvantage of handling the microphone and transmitter is more than offset by the user's improved ability to understand speech when background competition makes ordinary listening difficult.

Both conventional amplification and assistive listening devices continue to be principal rehabilitative resources for elderly persons with hearing impairment. Each method has associated advantages and disadvantages. Therefore, elderly persons must be evaluated carefully to ensure that the option ultimately selected is appropriate and helpful to their lifestyle.

CONCLUSIONS

In summary, several conclusions can be made about the effects of aging on central auditory processing. First, the interaural asymmetry characterizing performance on linguistically based DL tasks increases systematically with age. The effect is accounted for partly by decline in cognitive abilities and partly by decline in the efficiency of interhemispheric transfer of information. Second, aging appears to affect hemispheric asymmetry in linguistic processing. Asymmetry favoring the left hemisphere gives way to attenuated, or even reversed, asymmetry in elderly persons. Third, aging appears to alter the topographic distribution of ERP amplitudes across the surface of the head. Fourth, binaural hearing aids may not be the best intervention strategy for some elderly persons. Finally, in addition to traditional amplification, assistive listening devices based on remote-microphone technology are another useful resource to assist elderly persons in overcoming the problems posed by presbycusic hearing loss.

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