Individual Differences in Behavioral and Electrophysiological Measures of Binaural Processing Across the Adult Life Span

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Purpose: The purpose of the present study was to examine individual differences in binaural processing across the adult life span.

Method: Sixty listeners (aged 23–80 years) with symmetrical hearing were tested. Binaural behavioral processing was measured by the Words-in-Noise Test, the 500-Hz masking level difference, and the Dichotic Digit Test. Electrophysiological responses were assessed by the auditory middle latency response binaural interaction component.

Results: No correlations among binaural measures were found. Age accounted for the greatest amount of variability in speech-in-noise performance. Age was significantly correlated with the Words-in-Noise Test binaural advantage and dichotic ear advantage. Partial correlations, however, revealed that this was an effect of hearing status rather than age per se. Inspection of individual results revealed that 20% of listeners demonstrated reduced binaural performance for at least 2 of the binaural measures.

Conclusions: The lack of significant correlations among variables suggests that each is an important measurement of binaural abilities. For some listeners, binaural processing was abnormal, reflecting a binaural processing deficit not identified by monaural audiologic tests. The inclusion of a binaural test battery in the audiologic evaluation is supported given that these listeners may benefit from alternative forms of audiologic rehabilitation.
the behavioral masking level difference (MLD). Inspection of individual data, however, revealed evidence of reduced binaural processing for 52% of the subjects.

The proportion of individuals with reduced binaural processing varies from an estimated 8% to 10% for binaural interference reported by Jerger et al. (1993), 20% in the McArdle et al. (2012) study, 52% in the Leigh-Paffenroth et al. (2011) study, and 82% in the Walden and Walden (2005) study. Differences in methodology (e.g., subject selection criteria) and differences in how reduced binaural performance was defined contribute to this wide range. There is increasing evidence that some adults have no binaural advantage and that as many as 46% of adults who are hearing impaired prefer a unilateral to a bilateral hearing aid fitting (Cox, Schwartz, Noe, & Alexander, 2011). The lack of routine clinical measurement of binaural performance and dependence on traditional audiologic rehabilitation methods (i.e., bilateral hearing aids) likely will be ineffective for these individuals, leading to consumer dissatisfaction in an already weak hearing aid market (e.g., 25% market penetration rate; Kochkin, 2009). This is particularly true for the extreme case of binaural interference, which results in excessive difficulty understanding speech and has been associated with a lack of benefit from bilateral amplification (Allen, Schwab, Cranford, & Carpenter, 2000; Carter et al., 2001; Chmiel, Jerger, Murphy, Pirozzolo, & Tooley-Young, 1997; Holmes, 2003; Jerger et al., 1993). The inclusion of some measure of binaural hearing at the initial audiologic evaluation would provide critical information for audiologic rehabilitation strategies in up to half of the patients fit with hearing aids (Cox et al., 2011).

Binaural processing begins at the level of the upper brainstem (Moore, 1991), but central auditory pathways are critical to normal performance for more complex binaural tasks (e.g., three-pair dichotic digits require some working memory; Lawfield, McFarland, & Cacace, 2011). The specific tests in the present study were chosen because of their sensitivity to central auditory deficits (McPherson & Starr, 1993; Musiciek, 1983; Olsen & Noffsinger, 1976; Strouse & Wilson, 1999; Wilson & Weakley, 2005), their resistance to high-frequency hearing loss (Jerger, Brown, & Smith, 1984; Strouse & Wilson, 1999), their clinical utility, and the availability of published data for adults with and without hearing loss (Wilson & Burks, 2005; Wilson, Moncreiff, Townsend, & Pillion, 2003).

In a series of studies, Wilson and colleagues (Wilson, 2003; Wilson & McArdle, 2007) developed a clinical word-in-noise (WIN) paradigm that assesses the ability of the listener to understand speech in a background of multitalker babble. The test provides a range of signal-to-babble ratios (S/B), resulting in a 50% WIN threshold, and test time is approximately 4 min per ear. Adults with sensorineural hearing loss show a wide range of performance but almost always have a WIN threshold well above that of adults with normal hearing (e.g., > 6 dB S/B; Wilson, 2003). The WIN protocol can be presented monaurally and binaurally (Wilson & Cates, 2008).

Behavioral binaural processing measures that may be sensitive to binaural processing deficits in adults include the MLD and dichotic speech recognition (Jerger, Chmiel, Allen, & Wilson, 1994; Leigh-Paffenroth et al., 2011; Olsen, Noffsinger, & Carhart, 1976; Roup et al., 2006). The MLD reflects the auditory system’s ability to make use of phase differences between the two ears to detect a signal in a background of masking noise and is a measure of binaural release from masking. On average, older adults exhibit MLDs that are consistent with those of younger adults (Dubno et al., 2008; Kelly-Ballweber & Dobie, 1984); however, some older adults have abnormally small MLDs (i.e., ≤ 8 dB; Leigh-Paffenroth et al., 2011; Wilson & Weakley, 2005). Dichotic speech recognition tests are used to measure the ability of the binaural system to integrate and segregate stimuli from the two ears. Dichotic speech recognition performance is affected by both auditory perceptual deficits (e.g., peripheral and central) and task-related cognitive factors (e.g., attention and memory; Jerger, Stach, Johnson, Loiselle, & Jerger, 1990; Strouse & Wilson, 1999). The Dichotic Digits Test (DDT) is administered with a response paradigm of either free recall (“Repeat all the numbers you hear”) or directed recall (“Repeat the numbers you hear in your left ear”). The free recall response paradigm can be affected by both auditory perceptual and cognitive factors (Speaks, Niccum, & Van Tasell, 1985), whereas the directed recall paradigm is affected primarily by auditory perceptual factors. Therefore, comparison of performance between the two response conditions allows for determination of subjects who perform poorly due to auditory perceptual deficits versus cognitive factors. For example, poorer performance in the free recall condition relative to the directed recall condition reflects the heavier cognitive load associated with free recall. In contrast, poor performance in both response conditions reflects auditory perceptual deficits because a reduction in the cognitive load did not result in an improvement in performance for the directed recall condition. Listeners typically have better scores for speech stimuli presented to the right ear than for speech stimuli presented to the left ear (i.e., a right-ear advantage; Kimura, 1961). Dichotic digit recognition is generally poorer with larger right-ear advantages for older adults than for younger adults (Strouse & Wilson, 1999; Wilson & Jaffe, 1996). These behavioral measures of binaural processing are one way to assess the binaural system clinically.

Another way to assess binaural processing is with auditory electrophysiology. Electrophysiological responses do not require active participation from the listener and reduce the effects of nonauditory factors such as cognition and attention, which can influence behavioral performance. Binaural processing can be measured electrophysiologically by the binaural interaction component (BIC). The BIC is the difference between the sum of the monaural response from each ear and the binaural response and is most robust for the auditory middle latency responses (AMLR) in the thalamocortical pathway (McPherson & Starr, 1993). Inhibitory mechanisms in the auditory system reduce the
neural response to a binaural signal, resulting in a smaller electrophysiological response to a binaural signal compared with the electrophysiological response to both monaural signals added together (Finlayson & Caspary, 1991). The AMLR BIC has been shown to be sensitive to binaural processing deficits (Jerger et al., 1993) and strongly correlated with behavioral MLDs (Leigh-Paffenroth et al., 2011).

The purpose of the present study was to examine individual differences in binaural performance for symmetrical pure-tone thresholds across the adult life span. Binaural performance was measured using both behavioral and electrophysiologic tasks, including (a) word recognition in noise (WIN), (b) dichotic speech recognition (DDT), (c) the behavioral 500-Hz MLD, and (d) the electrophysiologic AMLR BIC. A secondary purpose was to determine if these measures of binaural processing would identify binaural deficits in a sample of adults with symmetrical hearing on the basis of pure-tone thresholds and word recognition in quiet (i.e., a standard audiologic protocol).

**Method**

**Subjects**

Sixty adults between the ages of 23 and 80 years (mean age = 54.8 ± 16.8 years) participated in the present study. Hearing thresholds ranged from normal (≤ 20 dB HL) to high-frequency mild to moderately severe sensorineural hearing loss. Figure 1 presents individual audiograms averaged across right and left ears for each subject. Inclusion criteria were (a) normal otoscopy; (b) tympanometric measures within normal limits (Roup, Wiley, Safady, & Stoppenbach, 1998; Wiley et al., 1996); (c) symmetrical thresholds within 15 dB; and (d) right-handedness, determined via the Edinburgh Handedness Inventory (Oldfield, 1971).

Subjects were recruited from the Mountain Home Veterans Affairs Medical Center Audiology Clinic, the East Tennessee State University student population, and the surrounding community of Johnson City, Tennessee. The present study was approved by the Institutional Review Board of the Mountain Home Veterans Affairs Medical Center and East Tennessee State University. All equipment was calibrated according to the appropriate standards (American National Standards Institute, 1987, 2004).

**Behavioral Measures**

**WIN Test.** Speech recognition-in-noise performance was assessed with the WIN Test (Wilson, 2003; Wilson & McArdle, 2007) from the Speech Recognition and Identification Materials, Disc 4.0 (Department of Veterans Affairs, 2006). For details regarding the development of the WIN Test, see Wilson (2003). In brief, the WIN Test is a 35-item test in which five monosyllabic words (Northwestern University Auditory Test No. 6; Tillman & Carhart, 1966) are presented at each of seven S/Bs in 4-dB intervals from 24 to 0 dB using multitalker babble. The WIN Test results in a threshold (dB S/B) at which 50% of words are correctly recognized, as derived by the Spearman–Kärber equation (Finney, 1952). The WIN was assessed for monaural right, monaural left, and binaural conditions. The WIN Test was presented from a compact disc (CD) player through a two-channel audiometer (Model 61, Grason Stadler, Eden Prairie, MN) to ER-3A insert earphones; the multitalker babble was fixed at 80 dB HL. The level of words on Northwestern University Auditory Test No. 6 varied from 24 to 0 dB S/B. The typical WIN protocol was extended such that two lists were presented in a random order for the three conditions (right, left, and binaural) for a total of six lists and a total of 10 words at each S/B. Testing was conducted in a sound booth, and the verbal responses of the subjects were scored as correct or incorrect by the examiner. Although no feedback was provided during testing, guessing was encouraged.

**DDT.** Dichotic digit recognition was measured using the DDT from the Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 1.0 (Department of Veterans Affairs, 1998). For details regarding the development of the DDT, see Strouse and Wilson (1999). In brief, the DDT is a 54-item stimulus set containing one-, two-, and three-pair digits (1–10, excluding the bisyllabic 7). Dichotic digit recognition performance was measured under the free recall, directed recall right, and directed recall left response conditions. In the free recall condition, subjects were instructed to repeat all digits heard, regardless of order. In the directed recall conditions, subjects were instructed to focus their attention on the directed ear and repeat the digits heard only in the target ear. The digit materials were presented from a CD player through a two-channel audiometer (Model 61, Grason Stadler) to ER-3A insert earphones at 70 dB HL. A brief familiarization procedure (five items) was used to acquaint the subjects with the dichotic digit task. Testing was conducted in a sound booth, and the verbal responses of the subjects were scored as correct or incorrect...
by the examiner. Although no feedback was provided during testing, guessing was encouraged.

500-Hz MLD. The 500-Hz MLD was measured using the paradigm developed by Wilson et al. (2003) and digitized on *Speech Recognition and Identification Materials* (Department of Veterans Affairs, 2006). In brief, the stimuli consisted of a 500-Hz tone and a 500-Hz broadband noise recorded on separate channels. For the signal-in-phase and noise-in-phase (S0N0) condition, the 500-Hz tone and noise were in phase in both ears. For the signal-out-of-phase and noise-in-phase (S0N0) condition, the 500-Hz tone was 180° out of phase between the ears while the noise was in phase in both ears. The range of signal-to-noise ratios (SNRs) for the S0N0 condition was −17 to 1 dB, and the range of SNRs for the S0N0 condition was −7 to −29 dB. The test consisted of 33 items presented in a pseudorandom order (11 no-tone conditions, 10 S0N0 conditions, and 12 S0N0 conditions) with a 4-s interstimulus interval. Subjects were instructed to verbally respond *yes* or *no* after each stimulus presentation to indicate whether they heard a tone. The MLD stimuli were presented from a CD player through a two-channel audiometer (Model 61, Grason Stadler) to ER-3A insert earphones at 70 dB HL. Testing was conducted in a double-walled sound booth, and the responses of the subjects were scored and recorded by the examiner. The Spearman–Kärber method (Finney, 1952) was used to determine S0N0 and S0N0 thresholds, and the MLD was calculated as the difference in threshold between the S0N0 and S0N0 conditions.

**Electrophysiologic Measure**

AMLRs were elicited by a 1000-Hz tone burst with a rise–fall time of 2 ms and a 1-ms plateau presented at 9.7/s monaurally to the right and left ears and binaurally. The stimuli were chosen based on case studies showing binaural interference with the AMLR BIC (Jerger et al., 1993). The stimulus level was calibrated acoustically with a Brüel and Kjær (Nærum, Denmark) 2250 sound level meter using an ER-3A insert earphone and a Brüel and Kjær 4152 artificial ear. The third-octave band levels of the 1000-Hz tone burst were 70 dB SPL. The AMLR stimuli were calibrated acoustically before data collection, on a weekly basis during data collection, and after data collection.

The SmartEP System (2.21, Intelligent Hearing Systems, Miami, FL) was used to obtain AMLR evoked potential recordings for each listener. The examiner monitored the electroencephalography noise during all AMLR recordings. Silver/silver chloride electrodes were attached to the high forehead (noninverting), earlobe of the test ear (left or right; inverting), and low forehead (ground) with impedances of ≤ 5 kΩ and within 2 kΩ across electrodes. The responses were amplified (100k) and band-pass filtered (30–250 Hz), and artifact rejection was set to 31 μV. Responses were averaged over 2,000 sweeps and then replicated. AMLRs were recorded in a double-walled sound booth with listeners comfortably seated in a reclining chair. Subjects were provided with reading material and were encouraged to use minimal movement when turning the pages.

Individual AMLR waveforms from the two replications of each condition (right, left, and binaural) were averaged. The monaural recording from the right ear was then added to the monaural recording from the left ear, resulting in single monaural and binaural waveforms. AMLR peaks Na, Pa, and Nb were identified for both the monaural and binaural waveforms. Na was identified as the most negative peak between 15 and 25 ms, Pa was identified as the most positive peak between 25 and 38 ms, and Nb was identified as the most negative peak following Pa. Waveform amplitude was measured peak to peak from Na to Pa and from Pa to Nb, and waveform latency was measured individually for Na, Pa, and Nb at the center of the peak. The binaural interaction waveform was derived by subtracting the binaural (*BIN*) response from the added monaural response: BIC = [(Right + Left) − *BIN*]. The peaks in the BIC waveform were marked as Na', Pa', and Nb'. BIC amplitudes and latencies were measured as described previously. All AMLR waves were identified and marked by the second author.

**Results**

**Relationships Among Measures of Binaural Processing and Age**

The potential relationships among behavioral and electrophysiologic measures of binaural processing and age were explored using Pearson’s correlational analysis. The correlation matrix for the seven variables is presented in Table 1; significant correlations are in bold. Because hearing varied among subjects, a partial correlational analysis controlling for hearing sensitivity was also conducted. Table 2 presents the partial correlations for age and the five binaural processing variables. Hearing sensitivity was defined as the four-frequency pure-tone average (PTA4) of thresholds at 500, 1000, 2000, and 4000 Hz. The PTA4 was chosen because it provides information about high-frequency hearing, and the PTA4 was significantly correlated with the traditional three-frequency pure-tone average. The PTA4s for the right and left ears were averaged for each individual subject in order to provide a single measure of hearing sensitivity. Figure 2 presents individual data as bivariate plots for each binaural measure as a function of age in years. In each panel, age is presented on the abscissa and each variable is presented on the ordinate; panel A shows the WIN binaural advantage, panel B shows the 500-Hz MLD, panel C shows the AMLR Na’–Pa’ BIC amplitude, panel D shows the dichotic free recall ear advantage, and panel E shows the dichotic directed recall ear advantage. The Pearson correlation coefficient is included in each panel.

Panel A of Figure 2 presents the WIN binaural advantage on the ordinate and age in years on the abscissa. Because the WIN Test results in an S/B threshold (50% point), lower thresholds indicate better performance. Assuming that binaural performance is typically better than monaural performance, the binaural advantage was calculated by subtracting the binaural WIN threshold from the best monaural
WIN threshold. A positive number indicates a lower WIN threshold in the binaural condition and, therefore, a binaural advantage. In contrast, a negative number indicates a lower WIN threshold in the best monaural condition and a binaural disadvantage. As can be seen in panel A of Figure 2, the WIN binaural advantage is significantly correlated with age ($r = .34$, $p = .008$) in that the magnitude of the WIN binaural advantage increased as a function of increasing age. However, by controlling for hearing sensitivity through partial correlational analysis, age was no longer correlated with the WIN binaural advantage. This suggests that as degree of hearing loss increases, monaural WIN thresholds decrease and listeners have greater room for improvement in the binaural condition. In fact, the PTA4 was significantly correlated with the WIN binaural advantage ($r = .34$, $p = .008$) in that the magnitude of the WIN binaural advantage increased as a function of increasing age.

Table 1: Pearson $r$ correlation matrix for the five dependent variables, age, and four-frequency pure-tone average (PTA4).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Age</th>
<th>PTA4</th>
<th>WIN BIN ADV</th>
<th>AMLR BIC</th>
<th>500-Hz MLD</th>
<th>Digit FR EA</th>
<th>Digit DR EA</th>
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<tbody>
<tr>
<td>Age Pearson $r$</td>
<td>1.0</td>
<td>.80</td>
<td>.34</td>
<td>.02</td>
<td>.08</td>
<td>.42</td>
<td>.04</td>
</tr>
<tr>
<td>Sig (two-tail)</td>
<td>0.00</td>
<td>.008</td>
<td>.88</td>
<td>.55</td>
<td>.001</td>
<td>.75</td>
<td></td>
</tr>
<tr>
<td>PTA4 Pearson $r$</td>
<td>1.0</td>
<td>.30</td>
<td>-.004</td>
<td>.06</td>
<td>.45</td>
<td>-.02</td>
<td></td>
</tr>
<tr>
<td>Sig (two-tail)</td>
<td>.02</td>
<td>.97</td>
<td>.67</td>
<td>.000</td>
<td>.89</td>
<td></td>
<td></td>
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<tr>
<td>WIN BIN ADV Pearson $r$</td>
<td>1.0</td>
<td>.05</td>
<td>.14</td>
<td>.12</td>
<td>.22</td>
<td></td>
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<tr>
<td>Sig (two-tail)</td>
<td>.72</td>
<td>.29</td>
<td>.36</td>
<td>.10</td>
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<tr>
<td>AMLR BIC Pearson $r$</td>
<td>1.0</td>
<td>.04</td>
<td>-.05</td>
<td>-.07</td>
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<tr>
<td>Sig (two-tail)</td>
<td>.74</td>
<td>.70</td>
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<td>500-Hz MLD Pearson $r$</td>
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<td>-.05</td>
<td>.08</td>
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<td></td>
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<tr>
<td>Sig (two-tail)</td>
<td>.68</td>
<td>.57</td>
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<tr>
<td>Digit FR EA Pearson $r$</td>
<td>1.0</td>
<td>.15</td>
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<tr>
<td>Sig (two-tail)</td>
<td>.26</td>
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<tr>
<td>Digit DR EA Pearson $r$</td>
<td>1.0</td>
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<td></td>
<td></td>
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<tr>
<td>Sig (two-tail)</td>
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</tbody>
</table>

Note: Significant ($p < .05$) correlations are presented in bold. WIN BIN ADV = words-in-noise binaural advantage; AMLR BIC = auditory middle latency response binaural interaction component; MLD = masking level difference; FR EA = free recall ear advantage; DR EA = directed recall ear advantage.

Table 2: Partial correlations for age and the five dependent variables while controlling for hearing loss (four-frequency pure-tone average).

<table>
<thead>
<tr>
<th>Variable</th>
<th>WIN BIN ADV</th>
<th>AMLR BIC</th>
<th>500-Hz MLD</th>
<th>Digit FR EA</th>
<th>Digit DR EA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age Partial $r$</td>
<td>.13</td>
<td>.08</td>
<td>.08</td>
<td>.07</td>
<td>.09</td>
</tr>
<tr>
<td>$p$ (two-tailed)</td>
<td>.34</td>
<td>.59</td>
<td>.56</td>
<td>.60</td>
<td>.54</td>
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</tbody>
</table>

Note: WIN BIN ADV = words-in-noise binaural advantage; AMLR BIC = auditory middle latency response binaural interaction component; MLD = masking level difference; FR EA = free recall ear advantage; DR EA = directed recall ear advantage.
Figure 2. Individual data presented as bivariate plots with age in years on the abscissa and each variable on the ordinate. 

(A) The words-in-noise (WIN) binaural advantage in dB signal-to-babble ratio (S/B), calculated as the difference between binaural thresholds and the best monaural threshold, on the ordinate. 

(B) The 500-Hz masking level difference in dB, calculated as the difference between the signal-in-phase and noise-in-phase (S_pN_o) and signal-out-of-phase and noise-in-phase (S_oN_o) thresholds, on the ordinate. 

(C) The auditory middle latency response binaural interaction component (AMLR BIC) amplitude in μV, calculated as the difference between the summed monaural responses and the binaural response, on the ordinate. 

(D) The dichotic three-pair digit free recall ear advantage, calculated as the difference between the score of the better ear and the score of the poorer ear, on the ordinate. 

(E) The dichotic three-pair digit directed recall ear advantage, calculated as the difference between the score of the better ear and the score of the poorer ear, on the ordinate. The lines in each panel represent the linear regression.

Pearson \( r = .34, p = .008 \)

Pearson \( r = .08 \)

Pearson \( r = .02 \)

Pearson \( r = .42, p = .001 \)

Pearson \( r = .04 \)
and binaural AMLRs, and the majority of subjects (90%) exhibited the expected positive BIC. In contrast, the BIC was absent or negative in six (10%) subjects. As can be seen in panel C of Figure 2, the regression line is essentially flat, indicating no relationship between the AMLR Na’–Pa’ BIC and age.

Panel D of Figure 2 presents individual three-pair dichotic digit ear advantages for the free recall response condition on the ordinate and age in years on the abscissa. The ear advantage is a difference score in which the left-ear score is typically subtracted from the right-ear score with the expectation that most listeners will exhibit a right-ear advantage. This method of determining ear advantage, however, obscures the absolute magnitude of ear advantage by not considering a left-ear advantage. Therefore, ear advantages in the present study were calculated by subtracting the percentage correct performance of the poorer ear from that of the better ear. As can be seen in panel D of Figure 2, the free recall ear advantage was significantly correlated with age (Pearson r = .41, p = .001) that the magnitude of the ear advantage increased as a function of increasing age. However, by controlling for hearing sensitivity through partial correlational analysis, age was no longer correlated with the free recall ear advantage. This suggests that as degree of hearing loss increases, the difference in dichotic performance between the ears also increases. In fact, the PT4A was significantly correlated with the free recall ear advantage (r = .45, p = .000) such that the degree of hearing loss increased, so did the free recall ear advantage. Inspection of the individual free recall dichotic data revealed one subject without an ear advantage in which performance between the two ears was equal, whereas the majority of subjects (98%) presented with ear advantages ranging from 1.9% to 54%.

Panel E of Figure 2 presents individual three-pair dichotic digit ear advantages for the directed recall response condition on the ordinate and age in years on the abscissa. As described previously, the ear advantage was calculated by subtracting the percentage correct performance of the poorer ear from that of the better ear. As can be seen in panel E of Figure 2, the regression line is essentially flat, indicating no relationship between the directed recall ear advantage and age. Inspection of the directed recall dichotic data revealed that 27% of subjects presented without an ear advantage in the directed recall response condition, whereas 73% of subjects presented with ear advantages ranging from 1.8% to 73%. A comparison of free recall and directed recall performance for three-pair digits demonstrated that 13% of subjects performed abnormally in both conditions, consistent with an auditory perceptual deficit.

### Regression Analysis

A regression analysis was conducted to determine if measures of binaural processing, age, and hearing sensitivity could predict binaural speech-in-noise performance (i.e., WIN binaural advantage). The predictor variables (age, PT4A, the 500-Hz MLD, the free and directed recall dichotic ear advantages, and the AMLR BIC) were simultaneously entered into the regression analysis. Table 3 presents the results of the regression analysis. For the dependent variable WIN binaural advantage, the multiple correlation was significant but low (r = .32 .41), accounting for 10% to 17% of the total variance. Age emerged as the primary predictor in the regression model and accounted for the majority of the variance associated with the WIN binaural advantage in that as age increased, the WIN binaural advantage also increased. The fact that age was strongly correlated with PT4A (r = .8, p = .000; see Table 1) suggests that both age and PT4A are primary predictors of the binaural advantage for speech-in-noise, accounting for 11% of the variance. The addition of the binaural measures into the regression model accounted for an additional 6% of the variance.

### Atypical Patterns of Individual Performance

Individual data were evaluated to identify subjects who performed abnormally on any of the four binaural measures. Abnormal performance was defined as (a) a lack of a WIN binaural advantage (i.e., a lower WIN threshold for the best monaural condition), (b) a 500-Hz MLD ≤ 8 dB (Wilson & Weakley, 2005), (c) three-pair dichotic digit recognition scores below the lower cutoff of the 99.7% confidence interval for both free and directed recall conditions (Strouse & Wilson, 1999), and (d) a lack of a BIC (BIC amplitude = 0 µV) or a negative BIC (binaural amplitude greater than monaural amplitude). Thirty-one subjects (52%) performed within the normal range on all measures of binaural hearing, and 19 subjects (32%) presented with only one abnormal test result. As a means of interest reliability, a pattern of binaural processing deficits was defined as any subject demonstrating abnormal results for at least two binaural measures. Individual results are presented in Table 4 for 10 subjects (20%) who fit this pattern. The 10 subjects ranged in age from 24 to 78 years, and all but two had a mild to moderate degree of hearing loss on the basis of the average PT4A. Abnormal patterns manifested in different ways for the 10 subjects who met this criteria (see Table 4). Seven of the 10 subjects (subjects 9, 12, 27, 32, 33, 35, and 45) exhibited abnormal results for two of the four binaural measures, and three subjects (subjects 6, 15,

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1Dichotic digit recognition performance consistent with an auditory-specific deficit (Jerger et al., 1990) was defined as performance that exceeded the lower cutoff of the 99.7% confidence interval for both free recall and directed recall conditions (Strouse & Wilson, 1999). The 99.7% confidence interval was calculated as the mean percentage correct recognition score ±3 SE.

2Summed monaural responses are typically larger than the binaural response, reflecting an inhibitory mechanism of the auditory system to binaural stimulation (e.g., Finlayson & Caspary, 1991), Therefore, the BIC was calculated by subtracting the binaural response from the summed monaural response. A BIC of 0 µV or a negative BIC were considered abnormal in that they reflect a lack of this inhibitory mechanism.
Table 3. Multiple linear regression results for the dependent variable words-in-noise (WIN) binaural advantage.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Predictor variable</th>
<th>r</th>
<th>R²</th>
<th>β</th>
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<tbody>
<tr>
<td>WIN binaural advantage</td>
<td>Age</td>
<td>.320</td>
<td>.103</td>
<td>.320*</td>
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<td></td>
<td>PTA4</td>
<td>.332</td>
<td>.111</td>
<td>.144</td>
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<td></td>
<td>Free recall EA</td>
<td>.336</td>
<td>.113</td>
<td>.054</td>
</tr>
<tr>
<td></td>
<td>Directed recall EA</td>
<td>.404</td>
<td>.163</td>
<td>.228</td>
</tr>
<tr>
<td></td>
<td>MLD</td>
<td>.414</td>
<td>.171</td>
<td>.093</td>
</tr>
<tr>
<td></td>
<td>AMLR BIC</td>
<td>.419</td>
<td>.176</td>
<td>.066</td>
</tr>
</tbody>
</table>

Note. PTA4 = four-frequency pure-tone average; EA = ear advantage; MLD = masking level difference; AMLR BIC = auditory middle latency response binaural interaction component.
*Significant (p < .05) standard coefficients (β values).

and 31) exhibited abnormal results for three of the four binaural measures. Eight subjects had below-normal performance on both the free and directed recall conditions of the DDT; seven out of the 10 had a smaller-than-normal MLD. Five of the 10 exhibited a binaural disadvantage on the WIN, and three of the 10 presented with absent or negative AMLR BICs.

Discussion

The present study examined individual performance as well as the relationship among measures of binaural processing in a group of right-handed listeners who varied in age and symmetrical hearing sensitivity. Results of binaural performance across listeners were as expected, with the majority of subjects demonstrating a binaural advantage for speech-in-noise performance (binaural WIN threshold lower than the best monaural WIN threshold), a binaural release from masking (MLDs ≥ 10 dB), right-ear advantages for the DDTs, normal auditory performance on both free and directed recall conditions of dichotic digit recognition, and present AMLR BICs. Fifty-two percent of subjects exhibited normal performance on all four measures of binaural hearing, and 32% presented with only one abnormal result. Binaural performance was consistent with previous binaural processing research for the majority of our subjects, including listeners with normal hearing and listeners who are hearing impaired (Leigh-Paffenroth et al., 2011), young and older listeners (Dubno et al., 2008; Grose, 1996), and subjects measured in complex listening environments (McArdle et al., 2012).

Potential relationships among the binaural measures were explored through correlational analyses. No correlations among the four binaural measures were found, suggesting that each measure represents a different aspect of binaural processing. Similar results were reported by Leigh-Paffenroth et al. (2011), except for their significant correlation between the AMLR BIC amplitude and the MLD. One difference between the studies was the large age range (23–80 years) in the present study. Both age and hearing status (PTA4) were positively correlated with the WIN binaural advantage and the dichotic digit free recall ear advantage. As age and PTA4 increased, the size of the WIN binaural advantage and the free recall ear advantage increased (Figures 2A and 2D). Age and PTA4 were not correlated with the 500-Hz MLD, the AMLR BIC, or the directed recall ear advantage. Partial correlational analysis while controlling for PTA4, however, revealed a lack of significant correlations between age and the WIN binaural advantage or free recall ear advantage. The results of the partial correlational analysis suggest that degree of hearing loss is responsible for the positive relationships of age with the WIN binaural advantage and free recall ear advantage.

Linear regression analysis was conducted to determine if the binaural measures, age, and PTA4 could predict the binaural advantage for speech-in-noise (WIN), which is a difficult listening environment for adults with hearing loss. The regression analysis indicated that individual differences in the binaural advantage for the WIN were associated primarily with individual differences in age. Age was

Table 4. Individual data for the 10 subjects exhibiting abnormal test results for at least two measures of binaural hearing.

<table>
<thead>
<tr>
<th>Subject number</th>
<th>Age (years)</th>
<th>PTA4 (dB HL)</th>
<th>BIC (µV)</th>
<th>MLD (dB)</th>
<th>WIN (dB S/B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>24</td>
<td>2.5</td>
<td>(0.18)</td>
<td>8</td>
<td>−0.4</td>
</tr>
<tr>
<td>9</td>
<td>39</td>
<td>10.0</td>
<td>(0.51)</td>
<td>8</td>
<td>(0.4)</td>
</tr>
<tr>
<td>12</td>
<td>42</td>
<td>41.3</td>
<td>(0.64)</td>
<td>(14)</td>
<td>−0.4</td>
</tr>
<tr>
<td>32</td>
<td>50</td>
<td>43.8</td>
<td>(0.13)</td>
<td>6</td>
<td>(2.4)</td>
</tr>
<tr>
<td>45</td>
<td>58</td>
<td>38.8</td>
<td>(0.20)</td>
<td>8</td>
<td>(2.8)</td>
</tr>
<tr>
<td>15</td>
<td>62</td>
<td>37.5</td>
<td>0</td>
<td>2</td>
<td>−0.4</td>
</tr>
<tr>
<td>33</td>
<td>72</td>
<td>45.0</td>
<td>(0.65)</td>
<td>(16)</td>
<td>−1.6</td>
</tr>
<tr>
<td>35</td>
<td>73</td>
<td>31.9</td>
<td>0</td>
<td>(16)</td>
<td>−1.6</td>
</tr>
<tr>
<td>31</td>
<td>76</td>
<td>44.4</td>
<td>(0.19)</td>
<td>8</td>
<td>−1.6</td>
</tr>
<tr>
<td>27</td>
<td>78</td>
<td>38.8</td>
<td>−0.27</td>
<td>(14)</td>
<td>−1.6</td>
</tr>
</tbody>
</table>

Note. Abnormal data points are presented in bold font, and data points within the normal range are presented in parentheses. PTA4 = four-frequency pure-tone average; BIC = binaural interaction component; MLD = masking level difference; WIN = words in noise; S/B = signal-to-babble ratio; RE = right ear; LE = left ear.
the only variable in the model that reached significance, accounting for 10% of the variability in the WIN binaural advantage. Hearing status (i.e., PTA4) accounted for an additional 1% of the variance. Given that age was strongly correlated with PTA4, it is likely that both are predictors of the binaural advantage for speech-in-noise performance. The results of this analysis suggest that as individuals age, they are better able to take advantage of binaural summation cues. Another possibility is that the younger listeners in the present study performed well for both monaural and binaural presentations and therefore had minimal binaural advantages. The fact that the binaural measures entered into the model were not significantly associated with the WIN binaural advantage, accounting for only an additional 6% of the variance, suggests that the measures of binaural hearing included in the present study are largely unrelated or that they tap into different binaural processes.

Inspection of the individual data from the present study revealed that 10 listeners did not exhibit the typical binaural advantage across measures. These 10 listeners demonstrated reduced binaural performance, which was defined as abnormal results for at least two experimental tasks. There was not a single pattern of atypical binaural performance that emerged, as abnormal results manifested in different ways across the 10 subjects identified. The most common abnormal result was below-normal performance for both free and directed recall on the DDT. Three-pair dichotic digit recognition performance for eight out of 10 subjects fell below the normal range for both response conditions, which is consistent with an auditory-based dichotic deficit (Jerger et al., 1990). For these individuals with binaural processing deficits, age and degree of hearing loss do not appear to be strong influencing factors. The 10 listeners varied greatly in age (24–78 years): Two were young adults, three were middle-aged adults, and five were older adults. In terms of degree of hearing loss, the two young adults presented with normal hearing, whereas the middle-aged and older adults presented with similar degrees of mild to moderate sensorineural hearing loss (PTA4 range = 32–45 dB HL). Overall, the 45 subjects with hearing loss in the study had PTA4s ranging from 23 to 58 dB HL, which is similar to the degree of hearing loss in the eight subjects with binaural processing deficits. Therefore, the outliers did not have the greatest amount of hearing loss, nor were they the oldest in this sample.

Results of dichotic digit recognition comparing performance between the two response conditions clearly showed that performance was reduced for most listeners in the free recall condition relative to the directed recall condition. Poorer recognition performance in the free recall response condition compared with the directed recall condition reflects cognitive factors and not peripheral auditory factors alone, such as hearing loss (Jerger et al., 1990). Individuals with a large dichotic ear advantage or those whose performance does not improve with a reduction in the cognitive load from the free condition to the directed condition potentially have other abnormal binaural hearing patterns; this factor is important to consider during bilateral hearing aid fittings. Using the criteria outlined by Strouse and Wilson (1999) for an auditory-specific dichotic deficit, eight out of 60 subjects (13%) were found to exhibit this pattern for three-pair digits. Strouse and Wilson (1999) reported similar findings, with six out of 180 subjects (3%) exhibiting an auditory-specific pattern of dichotic digit recognition. Seven of the eight subjects from the present study exhibiting this auditory-specific performance deficit were among those categorized as demonstrating abnormal binaural processing (defined previously; see Table 4). Individuals with auditory-specific dichotic deficits have been shown to exhibit speech recognition-in-noise deficits and a lack of benefit from bilateral amplification (e.g., Carter et al., 2001). The results of the present study support the clinical use of dichotic speech recognition measures to assess binaural processing.

WIN thresholds ranged from 0 to 21.6 dB S/B across subjects and conditions. Wilson et al. (2003) reported analogous results in their group of listeners who were hearing impaired. The range of performance for the best monaural and binaural conditions from the present study was quite variable, likely reflecting the large age range and variability in hearing sensitivity. Regardless, the range of WIN binaural advantages (best monaural threshold minus the binaural threshold) for the majority of subjects (57%) was relatively small, ranging from 0.4 to 5.2 dB S/B. A handful of subjects (11, or 18%) presented with no difference in WIN thresholds between the best monaural and binaural conditions. This has been referred to as binaural indifference (Rothpletz et al., 2004), where performance in the binaural condition is neither better nor worse than performance in the monaural condition. Last, 14 subjects (23%) presented with binaural interference, in which the WIN threshold of the binaural condition was poorer than the WIN threshold of the best monaural condition. Five of these 14 were among those categorized as demonstrating abnormal binaural processing (defined previously; see Table 4). Individuals without a binaural advantage for speech understanding in background noise may experience difficulty in segregating the signal of interest from background noise, which will likely affect the success of intervention strategies such as binaural amplification (Carter et al., 2001; Holmes, 2003).

MLDs ranged from 2 to 20 dB for the present group of listeners, who varied in age from 23 to 80 years. Wilson and Weakley (2005) found similar results across decade age groups from 20 to 80 years of age. Individual data, however, revealed 12 subjects (20%) from the present study who exhibited smaller-than-normal MLDs (≤ 8 dB). Seven of the 12 subjects with abnormally small MLDs were among those categorized as demonstrating abnormal binaural processing (defined previously; see Table 4). Individuals with little or no release from masking on the MLD test lack the ability to take advantage of binaural cues and therefore may not perform as well with bilateral hearing aids, particularly in noise (Dubno et al., 2008).

AMLR BIC amplitudes for Na’–Pa’ ranged from −0.62 to 1.52 μV. Leigh-Paffenroth et al. (2011) reported similar results for middle-aged and older adult listeners. Similar to the results from the DDT and the MLD, the
individual AMLR results revealed six subjects (10%) with abnormal BICs, three with absent BICs, and three with negative BICs (i.e., binaural responses larger than monaural responses). Three of the six subjects were among those categorized as demonstrating abnormal binaural processing (defined previously; see Table 4). The lack of an AMLR BIC is yet another indication of the inability of the auditory system to make use of binaural cues and may reflect behavioral difficulties understanding speech-in-noise (Jerger et al., 1993). Electrophysiologic measures should be considered for a binaural test battery due to the reduced effects of attention and nonauditory cognitive factors that can influence behavioral test performance, especially in older adults.

The binaural hearing tests used in the present study have been shown to be sensitive to central auditory deficiencies, resistant to high-frequency hearing loss, and clinically applicable. Clinical experience would suggest, however, that these tests are not used on a routine basis. The results from the present study demonstrate that a binaural test battery with acoustically complex and challenging measures was able to identify individuals with reduced binaural processing. A growing body of evidence from multiple case studies (Carter et al., 2001; Holmes, 2003; Jerger et al., 1993) and larger sample studies (Köbler et al., 2010; McArdle et al., 2012; Walden & Walden, 2005) indicates that individuals with reduced binaural performance or binaural interference reject bilateral amplification and prefer unilateral amplification. Humes et al. (2012) found emerging evidence of auditory effects due to aging in a detailed review of the current literature. The standard clinical test battery of pure-tone thresholds and monaural word recognition did not capture the potential effects of age on binaural processing. This is important regardless of whether age, either alone or in combination with hearing and cognition, has an effect on auditory function.

For example, subject 32 from the present study fit this clinical profile. He was a 50-year-old man with a mild to moderately severe sensorineural hearing loss and had symmetric pure-tone thresholds and symmetric word recognition performance in quiet. Thus, he was fit with bilateral amplification. As seen in Table 4, however, he exhibited reduced binaural performance on two binaural measures. When asked about his hearing aid use, he indicated a preference for wearing only the left hearing aid unless he had an appointment with the audiologist, when he wore the right hearing aid. Subject 32 reveals the need to measure binaural performance to identify patients who do not fit the typical binaural processing profile at the audiologic evaluation.

Conclusions

The benefits of binaural hearing are well known and have been studied widely in listeners with normal hearing (Brooks, 1984), listeners with hearing impairment (Haggard & Hall, 1982; Leigh-Paffenroth et al., 2011), and listeners who are aging (Dubno et al., 2008). Because binaural hearing is advantageous to the majority of individuals, deficits in binaural processing are rarely considered in the clinical assessment of auditory function. Standard monaural clinical measures, however, are almost always followed by bilateral hearing aid fittings that may not benefit, or may even be detrimental to, patients with unpredictable binaural processing deficits. Therefore, how a listener with bilaterally symmetrical hearing loss will respond to bilateral amplification cannot be accurately predicted on the basis of monaural measures alone. Evidence of deficits in binaural processing is beginning to emerge and to increase our knowledge of factors that likely contribute to poor audiologic rehabilitation outcomes among adult listeners (Carter et al., 2001; Leigh-Paffenroth et al., 2011; Ross, Takako, Tremblay, & Picton, 2007). Rather than maintaining the status quo with clinical measures that fail to provide relevant diagnostic information (Wiley & Stoppenbach, 1997), the clinical test battery should evolve to include tests that are acoustically complex, competitive in nature, and presented both monaurally and binaurally so that a patient-centered approach to audiologic rehabilitation can be developed. Future research is planned that incorporates a binaural test battery with patient-centered audiologic rehabilitation strategies. The goal of this research is to merge diagnostics, rehabilitation, and outcome measures, thereby improving individual audiologic outcomes for patients with binaural processing deficits.

Acknowledgments

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References


Department of Veterans Affairs. (1998). Tonal and speech materials for auditory perceptual assessment (Disc 1.0) [CD]. Mountain Home, TN: VA Medical Center.


