Behavioral and Electrophysiologic Binaural Processing in Persons with Symmetric Hearing Loss
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Abstract

Background: Binaural hearing improves our ability to understand speech and to localize sounds. Hearing loss can interfere with binaural cues, and despite the success of amplification, ~25% of people with bilateral hearing loss fit with two hearing aids choose to wear only one (e.g., Brooks and Bulmer, 1981). One explanation is reduced binaural processing, which occurs when the signal presented to one ear interferes with the perception of the signal presented to the other ear (e.g., Jerger et al, 1993). Typical clinical measures, however, are insensitive to binaural processing deficits.

Purpose: The purpose of this study was to determine the extent to which behavioral measures of binaural performance were related to electrophysiological measures of binaural processing in subjects with symmetrical pure-tone sensitivity.

Research Design: The relationship between middle latency responses (MLRs) and behavioral performance on binaural listening tasks was assessed by Spearman’s rho correlation analyses. Separate repeated measures analyses of variance (RMANOVAs) were performed for MLR latency and MLR amplitude.

Study Sample: Nineteen subjects were recruited for the present study based on a clinical presentation of symmetrical pure-tone sensitivity with asymmetrical performance on a word-recognition in noise test. This subpopulation of patients included both subjects with and subjects without hearing loss.

Data Collection and Analysis: Monaural and binaural auditory processing was measured behaviorally and electrophysiologically in right-handed subjects. The behavioral tests included the Words-in-Noise test (WIN), the dichotic digits test (DDT), and the 500 Hz masking level difference (MLD). Electrophysiological responses were measured by the binaural interaction component (BIC) of the MLR. The electrophysiological responses were analyzed to examine the effects of peak (Na, Pa, and Nb) and condition (monaural left, monaural right, binaural, and BIC) on MLR amplitude and latency.

Results: Significant correlations were found among electrophysiological measures of binaural hearing and behavioral tests of binaural hearing. A strong correlation between the MLD and the binaural Na-Pa amplitude was found (r = .816).

Conclusions: The behavioral and electrophysiological measures used in the present study clearly showed evidence of reduced binaural processing in ~10 of the subjects in the present study who had symmetrical pure-tone sensitivity. These results underscore the importance of understanding binaural auditory processing and how these measures may or may not identify functional auditory problems.

Key Words: Auditory evoked potentials, binaural processing, speech perception, hearing loss

Abbreviations: BIC = binaural interaction component; BIN = binaural; DDT = dichotic digits test; HI = hearing impaired; ILD = interaural level difference; ITD = interaural time difference; RMANOVA = repeated measures analysis of variance; MLD = masking level difference; MLR = middle latency response; MMSE = mini mental state exam; NH = normal hearing; SNR = signal-to-noise ratio; S_p N_o = signal in phase and noise in phase; S_p N_o = signal out of phase and noise in phase; WIN = Words-in-Noise test

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Based on the literature, it is suspected that a subset of the clinically hearing-impaired population has undiagnosed binaural processing problems, which may interfere with the ability to process auditory signals from the two ears (Arkebauer et al., 1971; Jerger et al., 1993; Walden and Walden, 2005; Walden, 2006). Furthermore, binaural processing problems likely are more prevalent in older compared to younger populations (Strouse et al., 1998). Binaural processing is the degree to which interactions take place between the two ears. If no interaction occurs between the two ears, then it is expected that the binaural system has been compromised. Binaural cues provide the basis for judgments on sound direction (e.g., interaural level differences [ILDs], interaural time differences, [ITDs]) (Bernstein, 2001) and may play an important role in speech in noise perception (Wambacq et al., 2007). Binaural processing problems have been reported in patients with multiple sclerosis (Hendler et al., 1990), dyslexia (McAnally and Stein, 1996), older subjects (Kelly-Ballweber and Dobie, 1984), children with suspected auditory processing disorders and learning disability (Gopal and Pierel, 1999), and children with chronic otitis media (Hall and Grose, 1993).

Individual cases of binaural processing problems have been reported in the literature for subjects with bilaterally symmetrical hearing loss (Chmiel et al., 1997; Carter et al., 2001). Chmiel et al. (1997) recorded behavioral and electrophysiological measures of binaural performance in a 90-yr-old patient with symmetrical sensorineural hearing loss who wore two hearing aids but could not use her hearing aids when in background noise. Binaural performance was measured by late cortical evoked potentials and word recognition. Unexpected performance differences between ears revealed poor performance for materials presented to the left ear compared to materials presented to the right in a dichotic listening task where she was asked to repeat sentences from each ear. The authors suggested that the binaural processing differences may be a result of age-related changes in the corpus callosum. Carter et al. (2001) reported four cases where patients with symmetrical sensorineural hearing loss preferred unilateral amplification to bilateral amplification. Binaural processing was measured by one-, two-, and three-pair dichotic digits. All four patients showed large deficits in performance for digits delivered to the left ear compared to digits delivered to the right ear. One explanation for the rejection of wearing two hearing aids is a binaural processing problem where the signal presented to one ear interferes with the perception of the signal presented to the other ear (Jerger et al., 1993; Silman, 1995; Allen et al., 2000). Typical clinical measures (e.g., pure-tone audiometry and word recognition in quiet), however, are insensitive to binaural processing problems. These case studies indicate that a clearer understanding of the binaural auditory system is important and that clinical measures of binaural hearing may be necessary for some patients prior to amplification decisions.

Behavioral measures of binaural processing include diotic and dichotic presentation of words, masking level differences (MLDs), and sound localization. Behavioral measures, however, require the subject to pay attention and respond subjectively to the task, which may not be ideal for older patients with attention or cognitive problems or for younger patients who cannot provide reliable behavioral responses (e.g., children with impaired cognitive abilities, etc.). An alternative to behavioral measures of binaural processing is the auditory evoked potential, an electrophysiological response to auditory stimuli. Electrophysiologic measures of binaural processing include MLDs (Musiek et al., 1989; Fowler and Mikami, 1996), binaural interactions (Kelly-Ballweber and Dobie, 1984), auditory steady-state responses (Wong and Stapells, 2004; Ishida and Stapells, 2009), and frequency following responses (Wilson and Krishnan, 2005). Electrophysiologic MLDs have been reported for the frequency following response (Wilson and Krishnan, 2005) and for the late cortical potentials in the auditory pathway (Fowler and Mikami, 1992a, 1992b, 1995; Kevanishvili and Lagidze, 1987). In a series of papers, Fowler and Mikami (1992a, 1992b, 1995, 1996) investigated the electrophysiological MLD and found cortical level MLDs (peaks N1, P1, N2, and P2) but not brainstem (auditory brainstem response [ABR]) or thalamocortical (middle latency response [MLR]) MLDs. Another electrophysiologic binaural measure, the binaural interaction component (BIC) has been recorded for the ABR, MLR, or cortical potentials in young and old subjects (Kelly-Ballweber and Dobie, 1984), in infants (Cone-Wesson et al., 1997; McPherson et al., 1989), in subjects with multiple sclerosis (Hannley et al., 1983; Hendler et al., 1990) and in children with central processing problems (Gopal and Pierel, 1999; Clarke and Adams, 2007). The BIC also has been used to study the effects of binaural hearing in the presence of noise (Weihing and Musiek, 2008).

An electrophysiologic measure of binaural processing would be advantageous in the assessment of patients with suspected binaural compromise (e.g., patients who prefer one hearing aid or patients who do not benefit from amplification in background noise). Electrophysiologic correlates of binaural perception not only have the advantage of reducing the influence of nonauditory factors (i.e., attention and cognition) but also present the possibility of assessing the auditory system at both subcortical and cortical levels. An objective electrophysiologic measure of binaural processing that is correlated with behavioral measures of binaural hearing would be advantageous in evaluating...
individuals who are unable to provide accurate behavioral responses (e.g., patients with cognitive deficits), particularly if this measure could be made at multiple levels of the auditory system.

**PURPOSE**

The primary purpose of the present study was to determine the extent to which an electrophysiological measure of binaural hearing was related to behavioral measures of binaural hearing in subjects with suspected asymmetrical speech recognition performance despite symmetrical pure-tone sensitivity. Asymmetrical speech recognition performance in the presence of symmetrical pure-tone sensitivity may be an indication of binaural processing problems.

**MATERIALS AND METHODS**

Monaural and binaural auditory processing was measured behaviorally and electrophysiologically in 19 right-handed subjects with symmetrical pure-tone hearing sensitivity. Subjects were selected for this study who presented clinically with suspected differences in performance between ears despite symmetrical pure-tone sensitivity. The suspected differences between ears were identified by asymmetrical Words-in-Noise (WIN) test performance of 5.6 dB. This subpopulation of patients included both subjects with and without hearing loss. The behavioral tests included the WIN test, the dichotic digits test (DDT), and the 500 Hz MLD. Electrophysiologic responses were measured by the BIC of the MLR. Data were collected in two 2 hr sessions over a 2 wk period. The first session included the audiological evaluation, questionnaires, and behavioral tests. The second session included the electrophysiological tests.

**Subjects**

The present study was approved by the Institutional Review Board of the Mountain Home Veterans Affairs Medical Center (VAMC) and East Tennessee State University, and all subjects signed an informed consent before participation began. A sample of 19 subjects was recruited from the Audiology Clinic at the VAMC for participation in this study. The subjects were recruited based on (1) asymmetrical word-recognition-in-noise performance where scores on the WIN test (Wilson, 2003) were 5.6 dB different between ears or (2) dissatisfaction with binaural hearing aid fitting determined by the Abbreviated Profile of Hearing Aid Benefit (APHAB) questionnaire (Cox and Alexander, 1995). The critical difference of 5.6 for the WIN test was based on the critical difference of 1.73 (Wilson, 2003) for the 99% confidence interval to detect a true difference. All subjects had symmetrical word recognition performance in quiet defined as 24% difference between ears for a 50-item word list (Carhart and Tillman, 1970). All subjects were right-handed (28, Edinburgh Handedness Inventory; Oldfield, 1971) and screened for auditory and medical conditions that may have confounded experimental test results. The mini mental state exam (MMSE; Folstein et al, 1975) was administered to determine if a listener was at risk for cognitive dysfunction. All scores on the MMSE were above the criterion for suspected cognitive dysfunction (i.e., 24).

A brief case history was obtained to determine if previous or current otic disease or neurological disorder required that the listener be excluded from the study. All subjects were tested with admittance measures and pure-tone audiometry. Tympanometric measures (Ytm [peak compensated static acoustic admittance], Vea [equivalent ear canal volume], and peak pressure) were within normal limits for younger (Roup et al, 1998) and older subjects (Wiley et al, 1996). Pure-tone thresholds were obtained using a clinical audiometer (Grason-Stadler, model GSI 61) with TDH-50P earphones calibrated according to ANSI 3.6 (American National Standards Institute, 2004) specifications for a Type 2 audiometer. All testing was conducted in a sound-treated booth (Industrial Acoustics Company, 1200 Series). Three subjects had hearing within normal limits from 250 to 4000 Hz, while 16 subjects had a range of sloping mild to severe symmetrical hearing loss. Interaural differences in threshold were 10 dB at all frequencies from 250 to 8000 Hz. The average audiogram is shown in Figure 1. The mean age for the normal hearing (NH) subjects was 41 yr (SD = 7 yr), and the mean age for hearing-impaired (HI) subjects was 61 yr (SD = 6 yr). Testing was completed in two sessions with audiological evaluation and behavioral testing in the first session and evoked potential testing in the second session.

**Behavioral Measures**

**WIN**

The WIN paradigm (Wilson, 2003; Wilson and McArdle, 2005) provides a measure of word recognition in multitalker babble across a range of signal-to-noise ratios (SNRs). The WIN paradigm was constructed of words from the Northwestern University Auditory Test No. 6 (NU 6) (Tillman and Carhart, 1966), which are presented at 7 SNRs from 24 to 0 dB in 4 dB decrements. Five words are presented at each level, and the babble level is fixed. The WIN paradigm was administered to the test ear under earphone with the level of the babble fixed at 80 dB SPL, and the level of the speech varied from 24 to 0 dB SNR in 4 dB steps. The materials were reproduced by CD and fed through an audiometer.
The experimental WIN protocol consisted of two lists presented in random order to the right ear, left ear, and binaurally for a total of six different lists for each listener and a total of ten words at each SNR (24 to 0 dB). Testing took place in a sound booth with the verbal responses of the listener scored by the examiner. Subjects were asked to repeat the words that they heard and were encouraged to guess.

Results from the WIN paradigm were quantified with the 50% point in terms of SNR based on the Spearman-Kärber equation (Finney, 1952). The SNR that corresponds to the 50% point on the WIN function was based on 10 words/level for a total of 70 words per condition (Wilson and McArdle, 2007).

**DDT**

The DDT used in the present study was constructed from the digitized digits on Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 1.0 (Department of Veterans Affairs, 1998). Development of the DDT materials is detailed in (Strouse and Wilson, 1999). Digits (1, 2, 3, 4, 5, 6, 8, 9, and 10) were presented in two 54-item lists that contained stimulus sets of one-, two-, or three-pair digits. A five-item practice set was used in each condition prior to test administration. The materials were recorded onto a CD, reproduced, and fed through an audiometer (Grason Stadler, Model 61) to an ER-3A insert earphone. The two lists were presented under different conditions: free recall, where subjects were asked to repeat the numbers that they heard without regard for ear, and directed recall, where subjects were directed to the target ear prior to each stimulus pair and asked to repeat only the digits presented to the target ear. Testing took place in a sound booth with the verbal responses of the listener scored by the examiner. Subjects were encouraged to guess. Dichotic listening is influenced by task-related cognitive factors such as attention and memory as well as sensory-related auditory factors such as peripheral or neural changes associated with an impaired auditory system. Performance on the directed-recall task is based primarily on audibility of the signal with minimal cognitive load. Performance on the free-recall task could be based on either audibility of the signal or cognitive factors. Comparison of the directed recall and free-recall conditions identified subjects who performed poorly based on cognitive factors instead of audibility factors.

**500 Hz MLD**

The 500 Hz MLD used in the present study was developed by Wilson et al (2003) and digitized on Speech Recognition and Identification Materials, Disc 4.0 (Department of Veterans Affairs, 2006). The stimuli were recorded in two channels with the noise held constant in one channel and the 500 Hz tone bursts presented on the second channel for the $S_{0}N_o$ and $S_{p}N_o$ conditions. The $S_{0}N_o$ condition consisted of the signal and the noise in phase in both ears. The $S_{p}N_o$ condition consisted of the signal 180° out of phase between the ears and the noise in phase in both ears. The range of SNRs for the $S_{0}N_o$ condition was –17 dB to 1 dB, and the range of SNRs for the $S_{p}N_o$ condition was –7 dB to –29 dB. The items were presented in a pseudorandom order with the highest SNR items presented first followed by the lower SNR items. The 33 test items consisted of 11 no tone conditions, 10 $S_{0}N_o$ conditions, and 12 $S_{p}N_o$ conditions. The interstimulus interval was 4 sec between the offset and onset of each consecutive item. Subjects were instructed to listen for the tone and to respond either “yes” or “no” to the presence of the tone after each presentation. The verbal responses of the listener were scored by the examiner. The $S_{0}N_o$ threshold and the $S_{p}N_o$ thresholds were calculated by the Spearman-Kärber method for use in determining the statistical threshold (Wilson et al, 1973). The MLD was calculated as the difference between the $S_{0}N_o$ threshold and the $S_{p}N_o$ threshold.

**Electrophysiologic Measures**

Binaural stimulation of the auditory system is not a simple summation of the monaural responses as demonstrated by measures of binaural interactions (Dobie and Norton, 1980; Levine 1981; Wrege and Starr, 1981; Ozdamar et al, 1986). Binaural interactions can be found in auditory evoked potentials of the brainstem (e.g., ABR wave V) and the thalamocortical pathway (e.g., Na-Pa and Pa-Nb of the MLR). Early work by Dobie and colleagues (Dobie and Berlin, 1979; Dobie
and Norton, 1980) showed clear binaural interactions as measured by the ABR and MLR in guinea pigs and in humans. The MLR BIC was chosen for the present study based on case studies of binaural interference (Jerger et al., 1993) and the robustness (i.e., larger amplitude) of the MLR BIC compared to the ABR BIC (Kelly-Ballweber and Dobie, 1984).

MLR

The purpose of recording MLRs to tap binaural processing was twofold. First, MLRs do not require the listener to respond behaviorally, so responses from subjects were not altered by attention. Second, the MLR provides a marked binaural interaction that is larger in amplitude than the ABR binaural interaction making it more likely that a BIC can be measured in subjects with hearing loss. MLR generator sites (auditory cortex, superior olivary complex, inferior colliculus, and medial geniculate body) are important for binaural hearing and well established as sites of binaural interaction (Goksoy et al, 2004).

MLRs were elicited by a 1000 Hz tone burst (2-1-2) presented at 9.7/sec monaural to the right ear, monaural to the left ear, and binaurally. Stimulus level was calibrated acoustically with a Bruel & Kjær 2250 sound level meter using an ER-3A insert earphone and a Bruel & Kjær 2 cm$^3$ coupler (DB-0138) attached to a Bruel & Kjær 4152 artificial ear. The 1/3-octave band levels of the 1000 Hz tone burst were 70 dB SPL. The MLR stimuli were calibrated acoustically before data collection, on a weekly basis during data collection, and after data collection.

Evoked potential recordings were obtained for each listener using the SmartEP System, 2.21 from International Hearing Systems. MLRs were recorded with the listener seated comfortably in a reclining chair in a double-walled sound booth. During the recording, reading material was propped on the listener’s lap and subjects were encouraged to turn pages with minimal movement. The electroencephalography (EEG) noise was monitored by the examiner during all MLR recordings. Ag/AgCl (silver/silver-chloride) electrodes were attached to the high forehead (Fz) (noninverting), earlobe of the test ear (A1 or A2) (inverting), and low forehead (ground) with impedances of ≤5 kohms. Earlobe electrode placement and careful monitoring of head position reduced the presence of the postauricular myogenic potential, which has been shown to interfere with the MLR. The responses were amplified (100k) and band-pass filtered (30–300 Hz), and artifact rejection was set to 31 μV. Responses were averaged over 2000 sweeps, and responses were replicated.

Raw waveforms from two replications of each condition (right, left, and binaural) were averaged, and then the monaural response from the right ear was added to the monaural response from the left ear. The peaks in the averaged waveforms were identified for each monaural MLR and for the binaural MLR. Amplitude was measured peak-to-peak from Na-Pa and Pa-Nb. Latency was measured individually for Na, Pa, and Nb. The Na peak was identified as the most negative peak between 15 and 25 msec; the Pa peak was identified as the most positive peak between 25 and 38 msec; and the Nb peak was identified as the most negative peak following Pa. The averaged binaural response was subtracted from the added monaural responses to derive the binaural interaction waveform, that is, (BIC) = ([R + L] - BIN). The peaks in the BIC waveform were marked as Na’, Pa’, and Nb’. Peak amplitudes were measured from the most positive point to the most negative point of the following trough. Peak latencies were measured at the center of the peak. All MLR waves were identified and marked by two independent experienced observers (authors E.L-P. and C.R.). In the two cases (2 waveforms out of 76) of disagreement between observers, the original raw waveform replications were used to identify peaks.

Data Analysis

The relationship between MLRs and behavioral performance on binaural listening tasks was assessed by Spearman’s rho correlation analyses, which is a non-parametric measure of the relationship between two ranked variables. The association between behavioral and electrophysiological measures was tested for the following: (1) the MLD and the MLR mean response amplitude, (2) the percent correct for the DDT and the MLR mean response amplitude, and (3) the signal-to-babble ratio corresponding to the 50% correct point on the WIN function and the MLR mean response amplitude. The electrophysiological responses were analyzed to examine the effects of peak (Na, Pa, and Nb) and condition (monaural left, monaural right, binaural, and BIC) on MLR amplitude and latency. Separate repeated measures analyses of variance (RMANOVAs) were performed for latency and amplitude. Differences between subjects based on pure-tone sensitivity were not analyzed statistically or important for the purposes of this study; however, potential differences in performance may exist and data will be reported separately for subjects with and without pure-tone sensitivity loss.

RESULTS

Behavioral Measures

WIN

Results for NH subjects revealed symmetrical performance between left and right ears with SNR ratios
of 5.9 (SD = 2) for the left ear and 6.4 (SD = 4) for the right ear. Similarly, results for HI subjects revealed equivalent performance between ears; however, these subjects required higher SNR ratios than the NH subjects. The SNR ratios were 13.3 (SD = 3) for the left ear and 12.6 (SD = 3) for the right ear for HI subjects. The subjects were selected based on asymmetrical WIN performance as measured in the clinic. The results from the WIN test in the present study revealed no asymmetrical performance, which could be explained by a practice effect from multiple WIN lists or laboratory versus clinic procedures (e.g., asking subjects to repeat their response if it was unclear to the investigator). Further, the experimental protocol doubled the number of trials per SNR (i.e., a double list per condition), which may be more representative of true performance. Binaural WIN performance was consistent with monaural performance, regardless of which ear was tested. The SNR ratio was 3.7 (SD = 3) for NH subjects and 13.0 (SD = 4) for HI subjects in the binaural condition. No significant differences were found between monaural and binaural scores or between left ear and right ear scores. The NH subjects (n = 3) performed better than the HI subjects (n = 16) as expected (Wilson, 2003).

**DDT**

The DDT was presented in a free-recall condition and a directed-recall condition. The directed-recall condition produced mean scores of ≈90% correct for all pairs, indicating that subjects were able to attend to the directed ear and ignore the stimulus in the nondirected ear. The remainder of the results will focus on the data from the free-recall condition. The data for the NH subjects (n = 3) will be presented separately from the data for the HI subjects (n = 16). All subjects completed the DDT. As expected, mean DDT performance declined and became more variable as the task difficulty increased from one-pair digits to three-pair digits as seen in Table 1. Individual listener’s performance is shown in Figure 2. The left panel of Figure 2 shows percent correct performance for the left ear as a function of percent correct performance for the right ear. The right panel of Figure 2 shows the individual data replotted with the percent correct performance for the poorer ear as a function of the percent correct performance for the better ear. Individual subject numbers are included in Figure 2 to illustrate data discussed below.

As seen in the top row of the left panel in Figure 2, DDT scores for the one-pair digits are near 100% correct for both ears for 15 of the 19 subjects. The four subjects who showed <85% on the one-pair dichotic digits are plotted by subject number (30, 19, 27, and 32). The two-pair digit scores reveal increasingly poorer performance, especially for digits presented to the left ear, and greater variability compared to the one-pair digits. A right-ear advantage is seen for most of the subjects for the two-pair dichotic digits. The three-pair digit scores show that most subjects exhibited the expected right-ear advantage 74% (14/19); however, 26% (5/19) showed a clear left-ear advantage (subjects 32, 8, 1, 22, and 27; see bottom left panel in Figure 2). Two of the subjects (32 and 27) had a left-ear advantage for all digit pairs.

The individual DDT data were replotted as percent correct performance for the poorer ear compared to percent correct performance for the better ear in order to observe ear advantage regardless of right or left ear (right panel, Figure 2). Traditional analysis of the right-ear advantage obscures the magnitude of the ear advantage by not considering the left-ear advantage. The one-pair digits show performance to be equivalent between ears for 90% (17/19) of the subjects but a clear ear advantage for two of the subjects (30 and 32). The two-pair digits reveal that most subjects had an ear advantage and with the three-pair digits, all subjects had an ear advantage. Again, ear advantage grew larger and performance became poorer as task difficulty increased from one-pair to three-pair digits.

**MLD**

The mean S_oN_o thresholds, mean S_oN_o thresholds, mean MLRs, and SDs are presented in Table 2 for subjects with normal pure-tone sensitivity (n = 3) and subjects with pure-tone sensitivity loss (n = 16). Individual MLRs were calculated by subtracting the S_oN_o threshold from the S_oN_o threshold. Table 2 shows that the mean MLD for normal-hearing subjects and for hearing-impaired subjects was >10 dB MLD regardless of pure-tone sensitivity, which was within the range of normal performance and as expected. One normal-hearing subject and two hearing-impaired subjects had MLDs ≤8 dB MLD, which was considered abnormal (Wilson et al, 2003).

**Electrophysiologic Measures**

**MLR**

Monaural and binaural MLRs were recorded for each subject. Responses were replicated, and the two replications were averaged to obtain a monaural left, monaural right, and binaural response for each subject. A t-test revealed no significant differences between the response amplitudes of the normal-hearing subjects and the hearing-impaired subjects; therefore, all subjects were analyzed without regard to pure-tone sensitivity status (i.e., normal or hearing impaired). The average response amplitudes, SDs, and number of subjects with a response are shown in Table 3. Averaged binaural responses were larger than averaged
monaural responses (see Table 3); however, 5/19 (26%) subjects showed a monaural response larger than the binaural response.

**BIC**

Binaural interaction components were identified separately by two observers. The average BIC response amplitudes, SDs, and number of subjects with a response are shown in Table 3. The average BIC response amplitudes were reduced by an average of 38% compared to the average monaural response amplitudes and by an average of 56% compared to the binaural response amplitudes. All subjects had monaural or binaural MLRs, and 74% (14/19) of subjects had MLR BICs. Monaural, binaural, and BIC waveforms from a typical subject with a clear BIC are shown in the left panel of Figure 3. Five of the 19 subjects showed no clear BIC; one of the five had no MLR for the right ear; therefore, a BIC could not be calculated. Monaural, binaural, and BIC waveforms from a subject with no clear BIC are shown in right panel of Figure 3.

RMANOVA tests were performed for latency and amplitude to examine the effects of peak (Na, Pa, and Nb) and condition (monaural left, monaural right, binaural, and BIC) on amplitude and latency. The RMANOVA for amplitude showed that the main effects of peak \( F(1, 12) = 5.114, p = .043 \) and condition \( F(3, 36) = 24.828, p < .001 \) were significant. The peak amplitude of Pa-Nb was significantly larger than the peak amplitude of Na-Pa. The post hoc analysis of condition showed that the binaural response amplitudes were larger than the monaural response amplitudes and that the BIC response amplitudes were smaller than the monaural and binaural response amplitudes \( (p < .05) \). The interaction of peak \( \times \) condition was not significant \( F(3, 36) = .697, p = .560 \).

The RMANOVA for latency showed that the main effect of peak \( F(2, 26) = 606.944, p < .001 \) was significant and expected based on the criteria for identifying peaks. The main effect of condition \( F(3, 39) = .384, p = .765 \) was not significant. The interaction of peak \( \times \) condition was significant \( F(6, 78) = 2.842, p = .049 \). Post hoc analysis of the interaction showed that the latency of NA was significantly shorter for the binaural response compared to the BIC.

**Relationships among Measures of Binaural Hearing**

The potential relationships among behavioral and electrophysiological measures of binaural hearing were investigated by Pearson's correlational analysis. Four significant correlations were found among MLRs and behavioral tests (MLDs and the DDT). First, the left ear Pa-Nb amplitude decreased as the SoNo threshold increased (i.e., higher SoNo thresholds equate to poorer detection) \( (r = -.488, p = .034) \). Second, the BIC Pa-Nb amplitude decreased as SoNo threshold increased \( (r = -.525, p = .037) \). Third, the performance on the two-pair dichotic digits presented to the left ear increased as Na response latency increased for the right ear \( (r = .484, p = .042) \). Fourth, the Na-Pa amplitude of the MLR BIC was significantly correlated to the dB MLD \( (r = .74, p = .002) \), as seen in Figure 4. As BIC Na-Pa amplitude decreased (reduced binaural interaction), the MLD decreased (poorer binaural detection). The best-fit line shows a linear relationship, which accounts for 55% of the variability in MLDs. The MLR BIC was evident in 14 of the 19 subjects in the study. The WIN scores (dB SNR) were not significantly correlated to any other measure of binaural hearing. The individual data are presented in Table 4 for the MLR, DDT, and MLD measures.

**DISCUSSION**

The purpose of the study was to determine the extent to which electrophysiological measures of binaural hearing were related to behavioral measures of binaural hearing. The results from the present study show that the amplitudes of the MLR BIC were strongly related behavioral MLDs. The current study extends the findings of Jerger et al (1993), Chmiel et al (1997), and Carter et al (2001), who reported individual cases

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**Table 1. Mean Dichotic Digit Performance (% correct) and SDs for Free Recall and Directed Recall Conditions**

<table>
<thead>
<tr>
<th></th>
<th>Free Recall</th>
<th>Directed Recall</th>
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<tbody>
<tr>
<td></td>
<td>One pair</td>
<td>Two pair</td>
</tr>
<tr>
<td></td>
<td>n</td>
<td>AS</td>
</tr>
<tr>
<td>NH</td>
<td>3</td>
<td>98 (3.5)</td>
</tr>
<tr>
<td>SNHL</td>
<td>16</td>
<td>92.1 (8)</td>
</tr>
</tbody>
</table>

Note: AD = monaural right; AS = monaural left; SNHL = sensorineural hearing loss.
of abnormal binaural function, and further shows significant relationships between behavioral measures and electrophysiological measures of binaural processing.

Behavioral Measures

The WIN test was used to provide a measure of word recognition in multitalker babble across a range of SNRs under monaural and binaural conditions. The WIN results from the present study were consistent with data presented by Wilson et al (2003) and Wilson and McArdle (2007) under monaural and binaural conditions for subjects with normal hearing and subjects with sensorineural hearing loss. Subjects with normal hearing had a mean SNR of 5.9 (SD = 2) for the left ear and 6.4 (SD = 4) for the right ear in the present study, which was consistent with a mean SNR of 4.8 dB (SD = 1.9) for the test ear in the monaural condition in the Wilson and McArdle (2007) study. Subjects with hearing loss had a mean SNR of 13.3 (SD = 3) for the left ear and 12.6 (SD = 3) for the right ear in the present study and 12.5 dB (SD = 2.9) for the test ear in the monaural condition in the Wilson and McArdle (2007) study. Mean SNRs for the binaural condition were similar to mean SNRs for the monaural condition for all subjects in the present study. The SNR ratio was 3.7 (SD = 3) for normal hearing subjects and 13.0 (SD = 4) for subjects with hearing loss. These SNRs are consistent with mean binaural SNRs of 3.7 (SD = 1.3) for normal hearing subjects and mean binaural SNRs of 11.3 (SD = 3.0) for subjects with hearing loss (Wilson and McArdle, 2007).

The mean DDT scores showed a progressive decline in performance as the level of task difficulty increased from one- to three-pair digits in the free recall condition for subjects with normal hearing. Mean percent correct scores for one-pair digits from NH subjects and from HI subjects in the present study were consistent with data from Wilson and Jaffe (1996). The mean percent correct for the three-pair digits from the NH subjects in the present study, however, were poorer than the data from Wilson and Jaffe (1996). The NH subjects in the present study scored 60% (SD = 1.2) and 86% (SD = 9.3) correct for the left and right ear, respectively, and the scores from the NH subjects in the Wilson and Jaffe study were 91% (SD = 5.9) and 94% (SD = 7.8) for the left and right ears, respectively. The NH subjects in the present study scored more than two SDs below the mean for the left ear in subjects with normal hearing from the young (<30 yr of age) normal in the Wilson and Jaffe (1996) study. One explanation is that the two NH subjects in the present study were older than the NH subjects in the Wilson and Jaffe study. In addition, the two NH subjects reported significant problems hearing and had asymmetrical WIN performance between ears in previous clinical audiological evaluations.

The mean three-pair digit scores for the HI group from the present study were 68% (SD = 13.2) and 72% (SD = 13.7) for the left and right ear, respectively, which were poorer than the mean scores from the 60–75-yr-old subject group in the Wilson and Jaffe study who scored 78% (SD = 1.9) and 88% (SD = 1.9) correct for the left and right ear, respectively. One reason for the discrepancy was the significant left-ear advantage

| Table 2. Mean S_oN_o Thresholds (dB SNR), S_oN_p Thresholds (dB SNR), and Mean MLDs (dB SNR) and SDs |
|---|---|---|---|---|
|   | n   | S_oN_o | S_oN_p | MLD  |
| NH  | 3   | -13.3 (5.0) | -24.0 (3.5) | 10.7 (2.3) |
| SNHL | 16  | -8.0 (2.3)   | -20.3 (4.1) | 12.3 (4.4) |
| All  | 19  | -8.8 (3.4)   | -20.8 (4.1) | 12.0 (4.1) |

Note: SNHL = sensorineural hearing loss.
for 26% of subjects in the present study. In a recent study (Iliadou et al, 2010), a left-ear advantage was reported for 60% of adults with auditory processing disorder and dyslexia compared to 13% for the control group and 47% for the dyslexia only group. The mean three-pair digit scores from the hearing-impaired group in the present study were similar to the three-pair digit scores from the oldest hearing-impaired group (70–79 yr of age) in Strouse and Wilson (1999), which were 65 and 78% correct for the left and right ears, respectively. The average age of the hearing-impaired subjects in the present study was 61 yr (SD = 6).

Overall, group-averaged data from the WIN test, the MLD, and the DDT were consistent with previously published literature in normal-hearing and hearing-impaired subjects. The individual data from the MLD and DDT, however, was not consistent with the literature for age-matched or hearing sensitivity-matched subjects. Several individual subjects showed evidence of abnormal binaural processing in behavioral measures; three subjects had a poor MLD (<8 dB); five subjects had left ear advantage for DDTs; and three subjects showed poor one-pair DDT scores (<84% correct for either ear). Individual data may lead to alternative rehabilitative strategies for patients with reduced binaural processing. Individual data will be considered below.

Electrophysiologic Measures

The MLR was recorded under three stimulus conditions: monaural left, monaural right, and binaural. Mean MLR Pa amplitude in response to binaural stimuli was larger than mean MLR Pa amplitude in response to monaural stimuli. Peak-to-peak amplitude data for monaural, binaural, and BIC responses were consistent with previously published data on monaural versus binaural MLRs in humans (Dobie and Berlin, 1979; McPherson et al, 1989; Kelly-Ballweber and Dobie, 1984). In the present study, the binaural Na-Pa amplitude increased by .37 μV in comparison to the monaural Na-Pa amplitudes and resulted in a 68% increase in amplitude for the binaural response. The binaural enhancement is similar to data reported by Weihing and Musiek (2008) of a .3 μV (50%) increase in BIN Na-Pa amplitude compared to monaural Na-Pa amplitude. The results from the present study also are in agreement with Ali and Jerger (1992) who measured monaural and binaural MLRs and reported only small differences in Pa and Pb between a group of older subjects with good speech understanding and a group of older subjects with poor speech understanding.

The individual MLR data, however, showed that 3/19 (16%) subjects showed a monaural response larger than the binaural response by at least 1 SE. One subject had a left ear monaural Na-Pa response larger than the binaural Na-Pa response; one subject had a left ear Pa-Nb response larger than the binaural Pa-Nb response; and one subject had a right ear Pa-Nb response larger than

| Table 3. MLR Average Amplitudes with SDs and Number of Subjects with a Response for Monaural Left (AS), Monaural Right (AD), BIN, and BIC |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | AS Na-Pa        | AS Pa-Nb        | AD Na-Pa        | AD Pa-Nb        | BIN Na-Pa       | BIN Pa-Nb       | BIC Na-Pa       | BIC Pa-Nb       |
| Mean           | 0.79            | 0.88            | 0.75            | 0.88            | 1.14            | 1.32            | 0.52            | 0.62            |
| SD             | 0.22            | 0.22            | 0.23            | 0.32            | 0.32            | 0.43            | 0.11            | 0.21            |
| Subject        | 19              | 19              | 18              | 18              | 19              | 19              | 14              | 16              |

Figure 3. Representative waveforms from two subjects are shown for the MLRs. Waveforms from top to bottom are monaural left (AS), monaural right (AD), BIN, and BIC (BIN = (R + L)), where BIN = the binaural response, R = the monaural right response, and L = the monaural left response. MLRs from a subject with typical responses are shown on the left, and MLRs from a subject with no BIC are shown on the right.
the binaural Pa-Nb response. The subject with the large right ear monaural Pa-Nb compared to the binaural Pa-Nb had a monaural response that was .39 mV larger than the binaural response, which was more than 3 SEs from the mean difference. In addition to the monaural to binaural amplitude differences, the BIC was absent in three subjects, and the right ear monaural MLR was absent in one subject. Kelly-Ballweber and Dobie (1984) reported that some of their subjects had no detectable BIC for the ABR and that results were similar for the MLR BIC but specific numbers of absent responses were not reported. The authors did report that the MLR data for the older subjects with hearing impairment were noisy. The MLRs in the present study were not noisy, but MLR BICs were undetectable in some subjects by two independent experienced observers. Dobie and Norton (1980) reported that one subject out of 16 showed no ABR BIC, but all subjects showed a MLR BIC.

The larger monaural response compared to the binaural response in some of the subjects in the present study was unexpected. Binaural stimulation of the auditory system is not a simple summation of the monaural responses (Dobie and Norton, 1980; Levine, 1981; Wrege and Starr, 1981; Ozdamar et al, 1986). The complex neural connections in the binaural auditory system permit both summation and inhibition to occur. Binaural processing is measurable by clinical auditory evoked potential tests, but a clear understanding of how hearing loss and aging affect the binaural response is lacking. The purpose of the present study was to investigate the relationships between binaural test measures in individual subjects suspected of having reduced binaural processing. This purpose led to subject selection that was different from previously published data from the tests used in the present study. The auditory pathways of the subjects in the present study may be different with regard to summation and inhibition than the auditory pathway of the general population. The unexpected monaural versus binaural differences found in the present study may or may not prove to be important in future investigations. The important outcome in the present study is the consistency with which some

Figure 4. The bivariate plot of masking level difference (dB SNR) (abscissa) and amplitude of the Na-Pa for the binaural interaction component (ordinate) for individual subjects. The dashed line represents the line of regression. The closed circles represent individual data.

Table 4. Individual Data Are Presented for the MLRs, DDTs, and the MLD

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Note: AD = monaural right; AS = monaural left.
subjects showed reduced binaural processing on two or more measures. Jerger et al (1993) reported case studies of four subjects who reported difficulty hearing but had normal pure-tone sensitivity and normal word recognition in quiet. Topographic brain maps were recorded from the scalp in response to an MLR stimulus paradigm in two of the subjects. In the first case, the MLR was reduced when the 1000 Hz tone burst was presented to the left ear and to both ears in comparison to stimulation to the right ear. The neural activity from the left ear stimulus apparently interfered with the neural activity from the binaural stimuli. In a second case, a subject with a left-sided cerebrovascular insult showed moderate to severe sensorineural hearing loss in the right ear and a mild to severe sensorineural hearing loss in the left ear. Aided word recognition was 75% correct in the left-aided condition, 8% correct in the right-aided condition, and 54% correct in the binaurally aided condition. The binaural word-recognition condition was expected to produce results at least as robust as the best monaural aided condition if no binaural interference occurred. In addition to abnormal binaural word recognition scores, the MLR was abnormal in that the response was larger for monaural left ear stimulation than binaural stimulation. Finally, a third case shows results from an 81-yr-old man with slightly asymmetrical sensorineural hearing loss, worse in the left ear. The monaural left ear MLR was absent, the monaural right ear response was present, and the binaural response was absent. Again, the binaural response should have been as large as possible as the best monaural response if no binaural interference occurred. The case studies presented by Jerger clearly show electrophysiological evidence of abnormal binaural processing similar to the individual data from the present study. In three of the Jerger cases and in four of the subjects from the present study, the electrophysiological responses from the left ear were abnormal compared to the binaural response.

**Relationships among Measures of Binaural Hearing**

Several relationships between electrophysiological responses and behavioral performance measures were found in the present study. First, the Pa-Nb amplitude for the left ear and for the BIC was lower for subjects with poorer S$_0$N$_a$ thresholds. The S$_0$N$_a$ threshold is recorded in dB SNR so “higher” S$_0$N$_a$ thresholds equate to poorer detection and reduced MLR amplitudes would be expected. Second, Pa response latency for the right ear increased as the performance on two-pair DDT improved. A scatterplot of the data (not shown) revealed considerable variability from the regression line and that the removal of three subjects resulted in a non-significant correlation ($p = .059$). The WIN scores (dB SNR) were not significantly correlated to any other measure of binaural hearing.

Finally, the correlation between the BIC Na-Pa amplitude and MLD from the present study was $r = .74$, $p = .002$. The BIC and the MLD both provide evidence of binaural integration of neurons, which first occurs in the superior olivary complex and continues to the inferior colliculus where evidence of binaural MLD phenomenon from single-unit studies has been found (Palmer et al, 1999, 2000). A significant relationship between the MLD and MLR BICs also was found by Hendler et al (1990) for control subjects and subjects with multiple sclerosis combined ($r = 0.41$, $p = .005$). As BIC Na-Pa amplitude decreased (reduced binaural interaction) the MLD decreased (poorer binaural detection and reduced release from masking). It is possible that these relationships between behavioral measures of binaural performance and the electrophysiological measures tap neural activation in the cortical auditory pathway, which is responsible for the MLR measures (Dobie and Norton, 1980) and likely is involved in MLR paradigms (Fowler and Mikami, 1996; Furukawa and Maki, 2006). The reduced ability to code temporal fine structure is one reason for reduced MLDs and poor MLRs.

Patients with multiple sclerosis often have been used to study the effects of neural lesions on measures of binaural processing. Hannley et al (1983) measured ABRs and MLDs in subjects with confirmed multiple sclerosis in order to determine the extent of the relationship between MLDs and the ABR. Results showed that the subjects with normal ABRs had MLDs within normal limits, the subjects with abnormal ABRs (specifically prolonged wave III latencies) had reduced MLD, and subjects with an absent wave III had no MLDs (i.e., showed no release from masking). The strong correlation between the MLR BIC and the behavioral MLD found in the present study are consistent with Hannley et al (1983).

Furukawa and Maki (2006) recorded MLRs from epidural electrodes over the left and right temporal lobes in guinea pigs in response to ITD and ILD paradigms. The MLR amplitude increased for level differences and time differences but not as a function of increasing intensity. So, the MLR is sensitive to ILD and ITD implying a close link between the neural generators of the MLR and the mechanisms underlying sound localization, both of which are important binaural functions. The Furukawa and Maki data support the correlation between the Na-Pa amplitude and the behavioral MLD found in the present study.

**Summary**

The present study was a first attempt to incorporate both behavioral and electrophysiological measures of binaural processing in subjects with suspected binaural
Compromise and symmetrical pure-tone thresholds. Case reports presented in the literature have described individuals who present with either neurological disease, positive history of neural lesions, or diagnosis of learning disability. One objective of the present study was to investigate binaural processing in a sample of subjects without specific neural impairment who may and may not be at risk for reduced auditory binaural processing. The behavioral and electrophysiological measures used in the present study clearly showed evidence of reduced binaural processing in listeners with symmetrical pure-tone sensitivity. In addition, some of the behavioral measures were significantly correlated with electrophysiological measures of binaural hearing; specifically, there was a strong correlation between the behavioral MLD and the BIC Na-Pa amplitude.

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