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An Electrophysiological Measure of Binaural Hearing in Noise

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Abstract

Background: A common complaint of patients with (central) auditory processing disorder is difficulty understanding speech in noise. Because binaural hearing improves speech understanding in compromised listening situations, quantifying this ability in different levels of noise may yield a measure with high clinical utility.

Purpose: To examine binaural enhancement (BE) and binaural interaction (BI) in different levels of noise for the auditory brainstem response (ABR) and middle latency response (MLR) in a normal hearing population.

Research Design: An experimental study in which subjects were exposed to a repeated measures design.

Study Sample: Fifteen normal hearing female adults served as subjects. Normal hearing was assessed by pure-tone audiometry and otoacoustic emissions.

Intervention: All subjects were exposed to 0, 20, and 35 dB effective masking (EM) of white noise during monotic and diotic click stimulation.

Data Collection and Analysis: ABR and MLR responses were simultaneously acquired. Peak amplitudes and latencies were recorded and compared across conditions using a repeated measures analysis of variance (ANOVA).

Results: For BE, ABR results showed enhancement at 0 and 20 dB EM, but not at 35 dB EM. The MLR showed BE at all noise levels, but the degree of BE decreased with increasing noise level. For BI, both the ABR and MLR showed BI at all noise levels. However, the degree of BI again decreased with increasing noise level for the MLR.

Conclusions: The results demonstrate the ability to measure BE simultaneously in the ABR and MLR in up to 20 dB of EM noise and BI in up to 35 dB EM of noise. Results also suggest that ABR neural generators may respond to noise differently than MLR generators.

Key Words: Auditory brainstem response, binaural hearing, central auditory processing disorder, diagnostics, middle latency response

Abbreviations: ABR = auditory brainstem response; ADD = attention deficit disorder; BD = binaural dominance; BE = binaural enhancement; BI = binaural interaction; BIC = binaural interaction component; CANS = central auditory nervous system; CAP = central auditory processing; (C)APD = (central) auditory processing disorder; EM = effective masking; ISI = interstimulus interval; KKS = King-Kopetzky Syndrome; LD = learning disabilities; MLD = masking level difference; MLR = middle latency response; MS = multiple sclerosis; OM = otitis media; SOC = superior olivary complex; SRT = speech recognition threshold

Sumario

Antecedentes: Una queja común de los pacientes con trastornos (centrales) de procesamiento auditivo es la dificultad para entender el lenguaje en medio de ruido. Dado que la audición binaural

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mejora el entendimiento del lenguaje en situaciones comprometidas de escucha, la cuantificación de esta habilidad en diferentes niveles de ruido puede generar una medida de gran utilidad clínica.

Propósito: Examinar el incremento binaural (BE) y la interacción binaural (BI) en diferentes niveles de ruido para las respuestas auditivas del tallo cerebral (ABR) y las respuestas de latencia media (MLR) en una población con audición normal.

Diseño de Investigación: Es un estudio experimental en el que los sujetos fueron expuestos a un diseño de medidas repetidas.

Muestra del Estudio: Quince mujeres adultas con audición normal sirvieron como sujetos. La audición normal fue evaluada por audiometría tonal pura y emisiones otoacústicas.

Intervención: Todos los sujetos fueron expuestos a 0, 20 y 35 dB de enmascaramiento efectivo (EM) con ruido blanco durante una estimulación con clics en forma monótica o diótica.

Recolección y Análisis de los Datos: Se midieron simultáneamente las respuestas del ABR y de las MLR. Las amplitudes pico y las latencias fueron registradas y comparadas en diferentes condiciones usando un análisis de varianza de medidas repetidas (ANOVA).

Resultados: Para el BE, los resultados de las ABR mostraron un incremento en 0 y 20 dB EM, pero no a 35 dB EM. Las MLR mostraron un BE a todos los niveles de ruido, pero el grado de BE disminuyó conforme aumentó el nivel de ruido. Para la BI, tanto las ABR como las MLR mostraron una BI a todos los niveles de ruido. Sin embargo, el grado de BI volvió a disminuir conforme aumento el nivel de ruido para las MLR.

Conclusiones: Los resultados demuestran la habilidad de medir el BE simultáneamente en las ABR y las MLR hasta 20 db de ruido EM y la BI hasta 35 dB de ruido EM. Los resultados también sugieren que los generadores neurales de las ABR pueden responder al ruido diferentemente de los generadores de las MLR.

Palabras Clave: Respuesta auditiva del tallo cerebral, audición binaural, trastorno de procesamiento auditivo central, diagnóstico, respuesta de latencia media

Abreviaturas: ABR = respuesta auditiva del tallo cerebral; ADD = trastorno de deficiencia de atención; BD = dominancia binaural; BE = incremento binaural; BI = interacción binaural; BIC = componente de interacción binaural; CANS = sistema nervioso auditivo central; CAP = procesamiento auditivo central; (C)APD = trastorno (central) de procesamiento auditivo; EM = enmascaramiento efectivo; ISI = intervalo inter-estímulo; KKS = Síndrome de King-Kopetzky; LD = trastorno del aprendizaje; MLD = diferencia del nivel de enmascaramiento; MLR = respuesta de latencia media; MS = esclerosis múltiple; OM = otitis media; SOC = complejo olivar superior; SRT = umbral de reconocimiento del lenguaje

BINAURAL HEARING IN NOISE AND ITS RELATIONSHIP TO PATHOLOGY

Binaural hearing provides numerous advantages over monaural hearing, including an improved ability for a listener to understand speech in noisy situations. This ability, sometimes called the "cocktail party effect," was first reported by Cherry (1953). Cherry speculated that it is possible not only for the auditory system to discriminate among stimuli on the basis of frequency and time differences, but also to use this information in the determination of whether a signal is speech or nonspeech. This discrimination of the speech signal could allow the auditory system to better separate speech from noise in compromised listening situations.

A number of studies have quantified the benefits obtained in speech understanding when one is listening binaurally in noise, speech babble, or reverberation. Pollack and Pickett (1958) found a 40% increase in word recognition ability in the presence of speech babble when listening was done binaurally as opposed to monaurally. Persson et al (2001) noted a similar binaural improvement of 20% and found that, in greater noise levels, a conversation could be understood when presented binaurally but not monaurally. Gelfand and Hochberg (1976) noted a 30% binaural advantage when speech was listened to with a 2-second reverberation time. Bronkhorst and Plomp (1992) and Hawley et al (2004) reported an approximately 2–4 dB improvement in speech recognition threshold (SRT) for binaural presentation of stimuli.

Various pathologies of the central auditory nervous system (CANS) exist and have as a symptom the reduced ability to efficiently process binaural stimuli. This phenomenon has been witnessed in neurologic-based disorders such as multiple sclerosis (MS). Cranford et al (1989) measured the precedence effect in a group of patients with MS and in a normal hearing control group. Results indicated that the accuracy of the experimental group was numerical poorer than controls by about 30%. Similarly, Levine et al (1993) noted that 40–70% of a group of patients with MS performed below normative values on an interaural discrimination task and that 8–11% of this group performed below norms on an interaural timing task. Furst et al (2000) also found decreased performance on an interaural discrimination and lateralization task in a group with MS when a lesion was located in the auditory pathway.

Binaural hearing deficits have also been noted in association with dyslexia, a disorder that has been shown to be closely related to anatomical variations in the CANS (Galaburda, 1985). McAnally and Stein (1996) demonstrated that subjects with dyslexia showed less release from masking in the masking level difference (MLD) paradigm than with normal hearing controls. Interestingly, Hill et al (1999) also examined MLDs in individuals with dyslexia and found no difference between their performance and that of a control group. The authors suggest that discrepancies between their findings and those of previous studies may be accounted for by the different stimuli that were used. Finally, Hari and Kiesila (1996) examined interaural timing discrimination in subjects with dyslexia by assessing an auditory illusion phenomenon that occurs during very short interstimulus intervals (ISIs). When the ISI was 150 msec, the subjects with dyslexia still perceived the illusion even though normal hearing subjects did not. This result indicates a difference in binaural processing between the two groups.

Studies investigating CAP in children with attention deficit disorder (ADD) or learning disabilities (LD) have also indicated a binaural hearing deficit. Pillsbury et al (1995), using the MLD paradigm, noted that subjects with ADD had higher than normal thresholds in both in- and out-of-phase conditions. McPherson and Davies (1995) measured the binaural interaction component (BIC) in the auditory brainstem response (ABR) and middle latency responses (MLR) in both a group with ADD and a control group. Results indicated that, for the BIC, Nb was about 15% greater in the control group. Gopal and Pierel (1999) also examined the ABR BIC in a group with LD, and found that—in the region of wave V—BIC amplitudes were significantly greater for the control group than for the experimental group.

Further clinical evidence for binaural hearing difficulties as a symptom of CANS pathology comes from otitis media (OM) research. Chronic OM can negatively affect CANS function and can lead to reduced performance on behavioral and electrophysiological auditory measures (Pillsbury et al, 1991; Hall et al, 1995). Hall and Grose (1993) measured the MLD in an experimental group that had had OM for an extended period and had been treated with pressure equalization tubes 1 month earlier. Results showed that the MLD was poorer in the OM group than in normal controls and that 40% of the experimental group and 0% of the control group scored beyond clinical normative values. Other studies have found no effect of OM on measures of binaural hearing, including the MLD and the BIC (Stollman et al, 1996). However, this latter research may be somewhat limited by atypical computation of the BIC and a large time span between episodes of OM and testing.

TOWARD AN ELECTROPHYSIOLOGICAL MEASURE OF BINAURAL HEARING IN NOISE

Given that binaural hearing has been shown to benefit hearing in noise and that patients with a variety of different (central) auditory processing disorders ((C)APD) show deficits in binaural processing, clinical measures of this ability may prove to be efficient measures of auditory pathology. There currently exist several behavioral measures that can be used to specifically assess auditory processing in the presence of ipsilateral or bilateral competition, some of which include Northwestern University word lists (NU–6) in noise (Olsen et al, 1975), Synthetic Sentence Identification with Ipsilateral Competing Message (Speaks and Jerger, 1965), speech MLDs (Bocca and Antonelli, 1976), auditory-figure-ground subtests of the SCAN (Keith, 1995), and the Listening in Spatialized Noise Test (Cameron et al, 2006). However, an exhaustive review of the literature failed to reveal the existence of a clinically feasible electrophysiological measure of binaural hearing in noise. An electrophysiological measure of this skill might show great utility over behavioral measures in its objectivity, its test efficiency, and its ability to be administered to difficult-to-test populations.

One way in which binaural hearing in noise could be measured electrophysiologically is with a variation of the BIC procedure. When researchers follow BIC protocols, in which evoked potentials are recorded during monaural left- and right-ear stimulation and then during binaural stimulation, at least two measures of binaural hearing can be computed. The first of these is the BIC index, in which the binaural waveform is subtracted from the sum of the left and right monaural waveforms, and the difference waveform is measured. Dobie and Berlin (1979) referred to the summed monaural waveform as the "predicted binaural" and the binaurally acquired waveform as the "true binaural." Generally, the amplitude of the predicted binaural is greater than the true binaural (however, see Decker and Howe, 1981, regarding issues of interaural asymmetry in evoked potential latency). It has been suggested that this reduction in amplitude of the true binaural relative to the predicted binaural may reflect a beneficial inhibitory process that occurs during binaural stimulation (McPherson and Starr, 1993). Debruyne (1984) has reported an alternative method for computing BIC, whereby the individual peak amplitude values of the monaural waves are added together and used to compute a BIC value. Note that a summing of the two monaural waveforms or a difference tracing is not necessary for this computation, only measurement of the peaks in the constituent waveforms. Debruyne's method would appear to have the added advantage of reducing the effects of interaural asymmetry in evoked potential latency. A modified version of this method is presented in the current paper, and this version will be referred to as a binaural interaction (BI) effect.

The second way in which binaural hearing in noise could be assessed using the BIC protocol is by comparing the constituent monaural indices separately to the binaural index. Therefore, instead of summing the monaural responses before making the binaural comparison, researchers could compare both the left- and right-ear responses individually to the binaural values. This comparison is similar in theory to research conducted by Decker and Howe (1981), in which researchers examined binaural processing by comparing the difference between individual left and right monaural waveforms with the binaural waveform. Examination of binaural processing in this way may, again, further reduce complications introduced by interaural asymmetry in evoked potential latency (Decker and Howe, 1981).

The present study differs from Decker and Howe's 1981 work in that difference waveforms were not calculated; only peak amplitudes for left, right, and binaural waveforms were compared. For the present investigation, this series of comparisons will be referred to as a binaural enhancement (BE) effect. Given that behavioral research has shown that binaural hearing is superior to monaural hearing in a variety of demanding listening situations (see earlier), we make the assumption for the present paper that, in the BE measure, greater amplitude of the binaural response over the monaural reflects greater binaural advantage.

Measurement of either BI or BE in noise may provide an objective electrophysiological measure of hearing in noise that could be used in the diagnosis of (C)APD. Examination of these indices in the simultaneously recorded ABR and MLR may be particularly advantageous. Because these potentials have different neural generators (Celesia et al, 1968; Hashimoto, 1982; Moller, 2000), their combined inclusion could increase the sensitivity of the measure to a wider range of pathology. Although little is known regarding the effect of noise on binaurally evoked potentials, a variety of research has examined the separate effects of binaural stimulation and noise on these responses.

BINAURAL PROCESSING AND/OR NOISE EFFECTS ON EVOKED POTENTIALS

BI effects on evoked potential recordings of the ABR were first reported by Jewett (1970) in studies of the cat. Jewett observed that when monaural recordings were algebraically summed, the summed amplitude of the first four waves equaled the amplitude of equivalent waves in binaural recordings, whereas the binaural recording for the fifth wave was less than this summed response. A binaural effect was subsequently shown in humans. For example, Dobie and Norton (1980) and Wrege and Starr (1981) found that the amplitude of summed monaural recordings was greater than that of the binaural recordings. Similarly, Debruyne (1984) reported a Binaural/Summed Monaural ratio for wave V that was less than 1, indicating smaller binaural amplitude than summed monaural. BE effects have also been reported in ABR wave V recordings. Both Starr and Achor (1975) and Ainslie and Boston (1980) noted that wave V was at least 0.1 microvolts larger during binaural presentations when compared to monaural.

The degree of BI has been quantified in the MLR as well. Dobie and Norton (1980) found significant BI in the Pa wave, while McPherson and Starr (1993) reported BI in both the Na and Pa. Debruyne (1984) noted a BIC ratio of less than 1 for the Na–Pa, indicating decreased amplitude of the binaural relative to the summed monaural. Numerous studies have also indicated that BE can be measured in the MLR. BE effects have also been reported in MLR recordings. Woods and Clayworth (1985) found that monaural potentials were nearly 80% as great in amplitude as were the binaural potentials. Versino et al (1991), Seki et al (1993), and Baez-Martin and Cabrera-Abreu (2000) all reported an enhancement of MLR amplitude in binaural conditions that was on the order of 0.15 to 0.25 microvolts.

The introduction of noise during evoked potential recordings has been shown to negatively affect the amplitude and latency of wave V of the ABR. Burkard and Hecox (1983) found that, for noise levels 20 dB effective masking (EM) and above, there was an increase in wave V latency and a decrease in amplitude with increasing noise level. Similar findings have been reported by Gott and Hughes (1989) and Burkard and Sims (2002). Various studies have also acquired information on the effect of noise on MLR indices. Smith and Goldstein (1973) examined the effects of ipsilateral white noise at several signal-to-noise ratios on the MLR. Results showed no effect of masking on latency of the potentials. However, there was a significant effect of ipsilateral noise on the Na–Pa amplitude. Gott and

Hughes also used ipsilateral white noise and found a small but significant latency effect. Interestingly, no effect on amplitude was noted. Such findings may differ from those of Smith and Goldstein as a result of the magnitude of noise that was applied. Gutnick and Goldstein (1978) examined the effect of contralateral noise on the MLR. Results showed that Na–Pa amplitude was smaller in some noise conditions.

Present Study—Measurement of BE and BI in Noise

The present study sought to establish a measure of BE and BI in noise using simultaneous acquisition of the ABR and the MLR in normal hearing individuals. Although many electrophysiological studies have investigated binaural processing and the effects of noise separately, there appears to be no account in the literature that has considered the interaction of the two. Our purpose in conducting this research was twofold. First, in general, it was of interest to know how well binaural processing, as reflected in the BE and BI of the ABR and MLR, was influenced by different levels of noise. Second, it was important to establish normative data that were based on a normal hearing population; those data could then could be used in sensitivity and specificity calculations in future studies. This step would begin the process of establishing this measure as a tool in the diagnosis of (C)APD.

METHODS

Subjects

Fifteen normal hearing female subjects were included in the present study (age: $M = 21.57$ years, $SD = 2.41$). To qualify as having normal hearing, subjects had to exhibit pure-tone air conduction thresholds for the octave frequencies between 250 and 8000 Hz better than or equal to 20 dB hearing level (HL). Information about pure-tone threshold interaural symmetry was also noted and is reported in the results. Additionally, subjects had to have distortion product otoacoustic emissions that fell above the Dartmouth-Hitchcock Medical Center's normative absolute amplitude values (Musiek and Baran, 1997) with a +9 signal-to-noise ratio at no fewer than five of six samples between 1187 and 3812 Hz per ear. All subjects denied any history of neurological involvement.

Equipment

Evoked Potential Unit

All subjects were tested while seated in a double-wall IAC sound booth. The ABR and MLR were recorded using a Nicolet Biomedical Spirit 2000 evoked potential unit. Electrodes were placed at Cz, C3, and C4 and were referenced to the nape of the neck; however, only data from Cz are reported in the present study. The ground electrode was located at the forehead. Impedance was maintained at below 8 kΩ with no more than a 3 kΩ difference between electrodes. A 40 msec time window was used so that both the ABR and the Na and Pa waves of the MLR could be recorded. A 20–1500 Hz analog filter with a 12 dB per octave roll-off was applied online to both the ABR and MLR. In addition, the MLR was digitally filtered offline from 20 to 250 Hz.

A 100 microsecond square wave, presented through the sound generator unit of the Spirit 2000, was used to generate a click. Clicks were presented both monaurally and binaurally at 60 dB SL re: click threshold in quiet. Clicks were presented at a rate of 9.7 per second. A total of 800 accepted trials were collected for each response. All responses were replicated, and the replications were averaged together. Stimuli were presented through insert ER-3A earphones, and a GN Resound open-ear dome was used instead of the standard foam insert so that the ear canal would not be occluded.

Noise Generation

White noise used in the present study was generated by a Grason-Stadler Instruments 61 audiometer. Noise was routed from the audiometer to two speakers located at +/− 45° azimuth inside the sound booth. The distance from the speakers to the opening of the subject's external auditory meati was 55 inches. Evoked potentials were recorded in three different noise conditions: quiet (i.e., 0 dB EM), 20 dB EM, and 35 dB EM.

Procedure

Before the study, click thresholds were obtained behaviorally with a Modified Hughson-Westlake procedure (Carhart and Jerger, 1959). These values were used as the reference for the click presentation level. Thresholds for left and right monaural stimulation were required to be within 5 dB of each other for subject inclusion. If there was a difference in left- and right-ear thresholds, the better threshold was used as the reference for monaural test procedures for both ears. This threshold was chosen to avoid a potential interaural difference at suprathreshold levels. Each subject's binaural threshold was used as the reference for presentation level for binaural conditions regardless of whether it was in agreement with the subject's monaural thresholds.

Thresholds were also obtained to the white-noise stimulus down to −10 dB EM, although these data were acquired only for descriptive purposes and were not used as a reference. As a means of ensuring midline lateralization of the clicks, subjects were also asked to point to the perceived location of a binaural click presented at 60 dB SL. Finally, to ensure that the masking noise induced the expected shift, click thresholds were also reestablished at both noise levels before beginning the experiment.

After these preliminary measurements were completed, the experiment was initiated. Clicks were always presented at 60 dB SL re: click threshold in quiet, regardless of the noise condition. In each noise condition, responses were collected for monaural left, monaural right, and binaural stimulation. Both stimulation mode and noise condition were counterbalanced across subjects. Typically, responses were replicated once as described earlier. However, if the replication was not in agreement with the initial response, a third response was acquired; next, the two waveforms that appeared to be most morphologically similar were retained. These two waveforms were then averaged.

Evoked Potential Measurements

For the ABR, latency and amplitude measurements were made for the wave V or IV–V peak. In quiet, the wave was defined as the positive-most value that occurred in the latency range of 5.5 to 6.5 msecs. The upper limit of this latency range was extended by 3 msecs for conditions that occurred in noise. Amplitude was initially measured both from baseline and from peak to proceeding trough. However, it was found that the appearance of wave VI in some waveforms would often interfere with accurate peak–trough amplitude measurement and yield considerable variation in the data. Therefore, the peak–baseline measurements were used in favor of the peak–trough values.

Binaural enhancement measures (ABR-BE) were derived by comparing individual left and right monaural peaks to the binaural peaks. Binaural interaction measures (ABR-BI) were computed by adding the individual amplitudes of two monaural peak values to obtain a summed monaural value that could then be compared to the binaural data. Because a true binaural difference waveform (i.e., predicted binaural subtracted from the true binaural) was not computed, no latency values are reported for analyses involving the summed monaural values.

For the MLR, latency measurements were made for both the Na and Pa waves. The Na wave was defined as the negative-most value that occurred between 12 and 21 msec and was consistent with Na wave morphology, and the Pa was the positive-most value that occurred between 21 and 38 msec and was consistent with Pa wave morphology. If a bifid wave was noted, the most positive peak was still used; however, the occurrence of bifid waves was relatively uncommon. Amplitude was recorded as the voltage difference between Na and Pa. Binaural enhancement (MLR-BE) and binaural interaction (MLR-BI) measures were computed in a manner identical to that described above for the ABR. Figure 1 contains examples of monaural and binaural MLR waveforms in the three noise conditions from one subject.

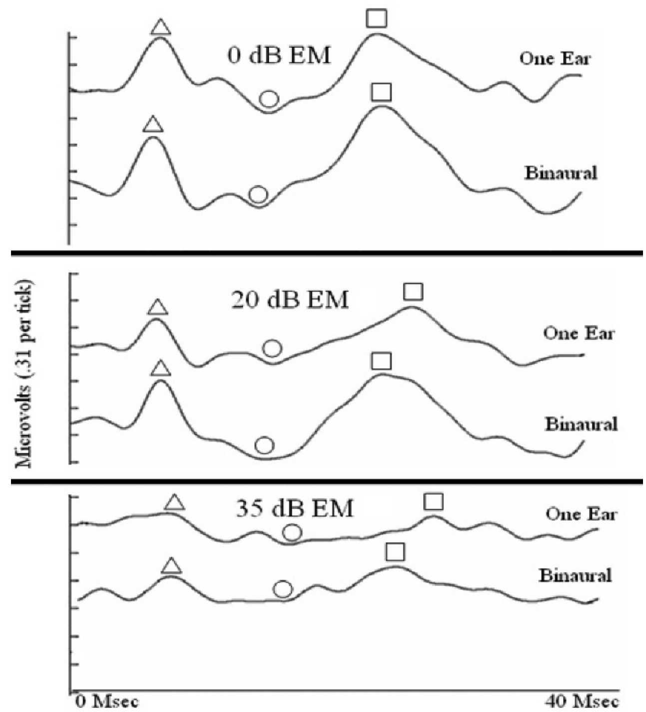

Figure 1. ABR and MLR monaural and binaural waveforms in the three noise conditions. Triangles indicate Wave V, circles the Na peak, and squares the Pa peak. Note that although a filtered ABR wave is presented here, measurements were made on the unfiltered waveform for this potential.

RESULTS[1]

Behavioral Threshold Descriptive Statistics

Table 1 contains descriptive statistics for subjects' monaural and binaural click behavioral thresholds in three noise conditions, as well as pure-tone threshold symmetry information (i.e., absolute value of the left minus the right pure-tone threshold averaged across all subjects). A repeated measures analysis of variance (ANOVA) with within-subject factors Ear (Left, Right, Binaural) and Noise (0, 20, 35 dB EM) was conducted. Results indicated a significant main effect for both Ear, $F(1.73, 24.22) = 4.47, p < .03$, and Noise, $F(1.72, 24.10) = 777.12, p < .001$, while an interaction between the factors did not reach significance. Paired t tests were conducted to determine which conditions differed significantly. Tests revealed that binaural thresholds were significantly better than right-ear thresholds ($p < .006$) and

Table 1. Descriptive Statistics for Behavioral Click Thresholds and Pure Tone Symmetry

Clicks (dBnHL)				Pure Tone Symmetry (dB HL)		
Noise	Ear	Mean	*SD*	Frequency	Mean	*SD*
0 EM	Left	3.67	3.52	250	2	2.54
	Right	4.33	3.20	500	1.33	2.29
	Binaural	2.33	3.20	1000	1.67	3.09
20 EM	Left	23.67	3.52	2000	2.33	3.20
	Right	24.00	2.07	4000	3	4.14
	Binaural	22.33	2.58	8000	3	4.55
35 EM	Left	38.33	3.09			
	Right	39.33	4.95			
	Binaural	37.67	3.72			

borderline-significantly better than left-ear thresholds ($p < .05$). All three noise conditions differed significantly from one another ($p < .001$), with thresholds becoming progressively worse as the noise level increased.

The mean threshold for the white noise stimulus was −9.64 dB EM ($SD = 1.34$). The mean threshold shift obtained in the two levels of noise relative to the 0 dB EM condition was also examined. Relative to 0 dB EM conditions, the mean threshold shift in 20 dB EM was 20.36 ($SD = 4.14$) for the left ear, 20.00 ($SD = 3.92$) for the right ear, and 20.36 ($SD = 3.65$) for the binaural condition. In 35 dB EM, the mean threshold shift was 35.00 ($SD = 5.19$) for the left ear, 35.36 ($SD = 4.99$) for the right ear, and 35.71 ($SD = 4.32$) for the binaural condition. These results indicate that, on average, the noise was shifting subjects' thresholds the expected amount. Additionally, all subjects were able to point to midline when the clicks were presented binaurally at 60 dB SL re: click threshold in quiet, consistent with lateralization of the clicks to midline.

ABR Statistics

Table 2 contains descriptive statistics for the ABR indices. For the ABR-BE measures of amplitude and latency, a repeated measures ANOVA was conducted; it included independent variables Ear (Left, Right, Binaural) and Noise (0, 20, 35 dB EM). For wave V amplitude, significant main effects of Ear, $F(2, 28) = 19.49$, $p < .001$, $\omega^2 = .23$, and Noise, $F(2, 28) = 53.46$, $p < .001$, $\omega^2 = .45$, were noted, in addition to a significant interaction between Ear and Noise, $F(4, 55.72) = 4.09$, $p < .007$, $\omega^2 = .09$.

Paired t tests were conducted to determine which conditions differed for those ANOVA factors that were significant. For the Ear factor, the left- and right-ear amplitudes were significantly lower than the binaural amplitude: left versus right $t(14) = .55$, $p = .59$; left versus binaural $t(14) = -4.59$, $p < .001$; right versus binaural $t(14) = -6.87$, $p < .001$. For the Noise factor, all three conditions differed significantly from one another, highlighting an inverse relationship between ABR amplitude and noise level: 0 versus 20 $t(14) = 7.59$, $p < .001$; 0 versus 35 $t(14) = 9.09$, $p < .001$; 20 versus 35 $t(14) = 3.50$, $p < .005$. Paired t tests and trends for the Ear and Noise interaction are summarized in Table 3 and Figure 2. The interaction is mainly the result of the lack of a significant difference between both monaural recordings and the binaural recording in 35 dB EM of noise only.

For wave V latency, a significant main effect of Noise was noted, $F(1.18, 16.56) = 37.58$, $p < .001$, $\omega^2 = .26$; however, both the Ear main effect, $F(1.84, 25.82) = 2.64$, $p = .09$, $\omega^2 = .02$, and the interaction between Ear and Noise were not significant, $F(2.80, 39.14) = 2.68$, $p = .06$, $\omega^2 = .04$. Paired t tests for the Noise factor indicated that all three conditions differed significantly, with latency becoming greater as noise levels increased: 0 versus 20 $t(14) = -9.71$, $p < .001$; 0 versus 35 $t(14) = -7.31$, $p < .001$; 20 versus 35 $t(14) = -4.14$, $p < .002$.

For the ABR-BI measure of amplitude (see Figure 3), a repeated measures ANOVA was conducted; it included independent variables Ear (Summed Monaural, Binaural) and Noise (0, 20, 35 dB EM). Considered here is the main effect for the Ear factor and the interaction between the Ear and Noise. All other analyses are statistically redundant with the ABR-BE results previously reported. Results indicated a significant main effect of Ear, $F(1, 14) = 6.12$, $p < .03$, $\omega^2 = .03$, and no significant interactions between Ear and Noise, $F(2, 28) = .53$, $p = .59$, $\omega^2 = .00$. Amplitude of the summed monaural condition was greater than that of the binaural.

MLR Statistics

Table 4 contains descriptive statistics for the MLR indices. For the MLR-BE measures of amplitude and latency, a repeated measures ANOVA was conducted; it included independent variables Ear (Left, Right, Binaural) and Noise (0, 20, 35 dB EM). Noted for Na–Pa amplitude were significant main effects of Ear, F(2,

Table 2. Descriptive Statistics for the ABR

		Wave V Latency Mean	Wave V Latency *SD*	Wave V Amplitude Mean	Wave V Amplitude *SD*
0 EM	Left	5.86	.168	.725	.289
	Right	5.86	.145	.721	.188
	Sum	-	-	1.45	.385
	Binaural	5.83	.135	1.27	.451
20 EM	Left	6.03	.200	.458	.255
	Right	6.19	.234	.437	.346
	Sum	-	-	.895	.439
	Binaural	6.15	.236	.845	.251
35 EM	Left	6.43	.561	.406	.269
	Right	6.37	.439	.313	.168
	Sum	-	-	.719	.338
	Binaural	6.71	.575	.525	.272

Note: Latency is shown in milliseconds and amplitude in microvolts.

28) = 55.57, p <.001, ω^2 = .35, and Noise, F(1.65, 23.08) = 49.22, p <.001, ω^2 = .37. A significant interaction was also noted between Ear and Noise, F(4, 56) = 3.35, p <.02, ω^2 = .02. Paired t tests were conducted to determine which conditions differed for those factors that were significant. For the Ear factor, the left- and right-ear amplitudes were significantly lower than the binaural amplitude: left versus right t(14) = −.52, p = .612; left versus binaural t(14) = −8.11, p <.001; right versus binaural t(14) = −8.11, p <.001. For the Noise factor, all three conditions differed significantly from one another, with amplitude decreasing as noise increased: 0 versus 20 t(14) = 5.88, p <.001; 0 versus 35 t(14) = 7.91, p <.001; 20 versus 35 t(14) = 5.86, p <.001. Paired t tests and trends for the Ear and Noise interaction are summarized in Table 5 and Figure 4.

So that the significant differences in the Ear and Noise interaction in MLR-BE could be better clarified, a series of paired t tests was conducted; these tests compared the magnitude of the difference between left/right monaural and binaural stimulation for each of the noise conditions. Therefore, six new variables were created: Mag0L/R (binaural minus monaural left/right in the 0 dB EM condition), Mag20L/R (binaural minus monaural left/right in the 20 dB EM condition), and Mag35L/R (binaural minus monaural left/right in the 35 dB EM condition). Results indicated that only Mag0L and Mag35L were significantly different, t(14) = 3.38, p <.006; in this case, the difference between left and binaural in 0 dB EM of noise was greater than the difference between left and binaural in 35 dB EM of noise.

For Na latency, no significant main effects or interactions were noted: Ear F(1.89, 26.52) = .51, p = .415, ω^2 = .00; Noise F(2, 28) = .186, p = .831, ω^2 = .00; Ear × Noise F(3.59, 50.24) = .454, p = .749, ω^2 = .00. Similarly, no significant main effects were noted for Pa latency: Ear F(2, 28) = 2.94, p = .069, ω^2 = .02; Noise F(2, 28) = .787, p = .465, ω^2 = .00. Although a significant interaction was noted between Noise and Ear for Pa, F(3.28, 45.86) = 3.14, p <.04, ω^2 = .03, no subsequent paired t tests were significant once the Bonferroni adjustment was performed.

Table 3. ABR-BE Paired *t* tests for Ear × Noise Interaction

		0 EM			20 EM			35 EM		
		Left	Right	Bi	Left	Right	Bi	Left	Right	Bi
0 EM	Left	-		*[a]	*		[b]		*	[b]
	Right	-	-	*[a]			[b]		*	[b]
	Binaural	-	-	-	*	*	*	*	*	*
20 EM	Left	-	-	-	-		*[a]			*[b]
	Right	-	-	-	-	-	[a]			*[b]
	Binaural	-	-	-	-	-	-	*	*	*
35 EM	Left	-	-	-	-	-	-	-		[a]
	Right	-	-	-	-	-	-	-	-	[a]
	Binaural	-	-	-	-	-	-	-	-	-

[a]Binaural enhancement comparisons.

[b]Binaural dominance comparisons.

Note: Binaural enhancement refers to superior binaural hearing over monaural within the same noise level. Binaural dominance refers to superior binaural hearing over monaural hearing measured in a lower noise level. For a more complete explanation of terms, refer to the introduction and discussion, respectively.

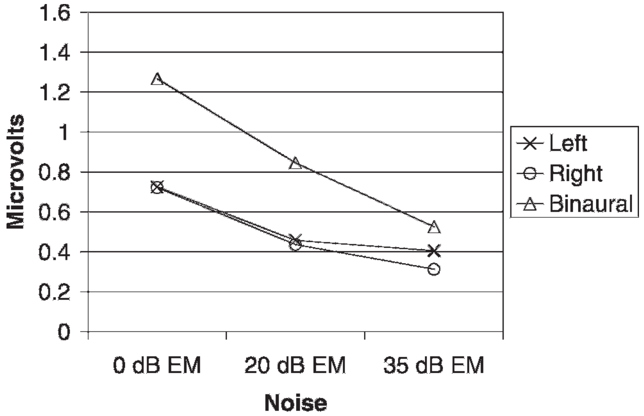

Figure 2. ABR-BE by ear and noise levels.

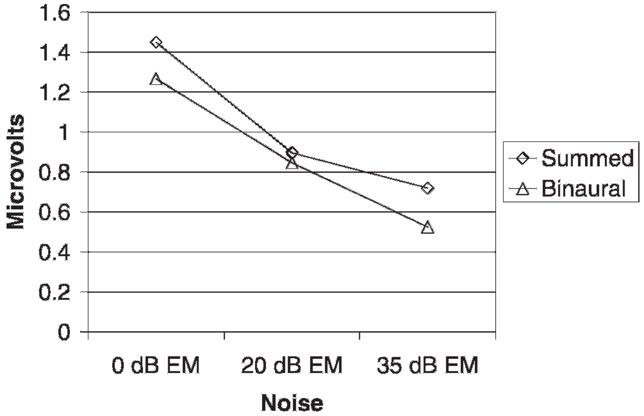

Figure 3. ABR-BI by ear and noise levels.

For the MLR-BI measure of amplitude, a repeated measures ANOVA was conducted; it included independent variables Ear (Summed Monaural, Binaural) and Noise (0, 20, 35 dB EM). Considered here is the main effect for the Ear factor and the interaction between the Ear factor with Noise. All other analyses are statistically redundant with the MLR-BE results previously reported. Results indicated a significant main effect of Ear, $F(1, 14) = 92.53$, $p < .001$, $\omega^2 = .21$, where the summed monaural amplitude was greater than binaural amplitude, and a significant interaction between Ear and Noise: $F(2, 28) = 4.06$, $p < .03$, $\omega^2 = .02$. Paired t tests and trends for this interaction are summarized in Table 6 and Figure 5.

So that the significant differences in the Ear and Noise interaction in MLR-BI could be better clarified, a series of paired t tests was conducted; these tests compared the magnitude of the difference between summed monaural and binaural for each of the noise conditions. Therefore, three new variables were created: Mag0 (summed monaural minus binaural in the 0 dB EM condition), Mag20 (summed monaural minus binaural in the 20 dB EM condition), and Mag35 (summed monaural minus binaural in the 35 dB EM condition). Results indicated that only Mag0 and Mag35 differed significantly: $t(14) = 2.95$, $p < .02$.

Interrater Reliability

Wave V, Na, and Pa for two randomly selected subjects were independently measured by a second researcher in order to compute interrater reliability. Each Ear × Noise condition was counted as a case in the raters' measurements, and then these cases were correlated across the two researchers. Results showed a significant relationship between raters for wave V latency ($r = .95$, $p < .001$), wave V amplitude ($r = .97$, $p < .001$), Pa latency ($r = .65$, $p < .004$), and Na–Pa amplitude ($r = .94$, $p < .001$). No significant correlation was noted for Na latency ($r = .36$, $p = .14$). However, the mean difference between raters on this measure was small in magnitude ($M = 0.93$ msec, $SD = 1.71$). Additionally, the strong correlation between raters on Na–Pa, which is dependent on identification of Na latency, suggests that this interrater variance is likely not meaningful.

Table 4. Descriptive Statistics for the MLR

		Na Latency Mean	Na Latency *SD*	Pa Latency Mean	Pa Latency *SD*	Na–Pa Amplitude Mean	Na–Pa Amplitude *SD*
0 EM	Left	16.14	2.12	25.15	2.09	.637	.183
	Right	16.30	2.05	24.28	1.71	.698	.156
	Sum	-	-	-	-	1.34	.304
	Binaural	15.28	1.82	24.72	1.44	1.00	.231
20 EM	Left	16.35	2.19	24.69	2.78	.525	.139
	Right	16.08	2.08	25.39	1.98	.518	.123
	Sum	-	-	-	-	1.04	.235
	Binaural	15.74	2.03	24.01	2.05	.790	.182
35 EM	Left	16.16	2.05	24.82	1.73	.379	.167
	Right	15.66	2.69	26.11	2.20	.374	.154
	Sum	-	-	-	-	.753	.268
	Binaural	16.04	2.71	24.41	1.49	.587	.207

Note: Latency is shown in milliseconds and amplitude in microvolts.

Table 5. MLR-BE Paired *t* tests for Ear × Noise Interaction

		0 EM			20 EM			35 EM		
		Left	Right	Bi	Left	Right	Bi	Left	Right	Bi
0 EM	Left	-		*[a]			*[b]	*	*	[b]
	Right	-	-	*[a]	*	*	[b]	*	*	[b]
	Binaural	-	-	-	*	*	*	*	*	*
20 EM	Left	-	-	-	-		*[a]			[b]
	Right	-	-	-	-	-	*[a]		*	[b]
	Binaural	-	-	-	-	-	-	*	*	*
35 EM	Left	-	-	-	-	-	-	-		*[a]
	Right	-	-	-	-	-	-	-	-	*[a]
	Binaural	-	-	-	-	-	-	-	-	-

[a]Binaural enhancement comparisons.
[b]Binaural dominance comparisons.
Note: Binaural enhancement refers to superior binaural hearing over monaural within the same noise level. Binaural dominance refers to superior binaural hearing over monaural hearing measured in a lower noise level. For a more complete explanation of terms, refer to the introduction and discussion, respectively.

DISCUSSION[2]

Amplitude Measures

The present study found a significant BE effect in both ABR-BE and MLR-BE, where peak amplitudes in binaural recordings were larger than those obtained in monaural recordings. For ABR-BE, this effect was dependent on noise level: binaural enhancement was present relative to at least one monaural recording in 0 and 20 dB EM, but not in 35 dB EM. For MLR-BE, the effect was also dependent on noise level; however, the pattern displayed was slightly different from that seen in ABR-BE. Unlike the ABR, where no BE was seen in 35 dB EM of noise, there was significant BE at *all* noise levels for the MLR. Therefore, the binaural amplitude was greater than the monaural amplitude in all noise conditions. The degree of BE (i.e., binaural minus monaural amplitude), however, did decrease as the noise level was increased from 0 to 35 dB EM relative to the left-ear monaural condition. It should be noted that, despite these findings, effect sizes computed for the ABR and MLR interactions were similar in magnitude even though the ABR interaction effect was numerically larger.

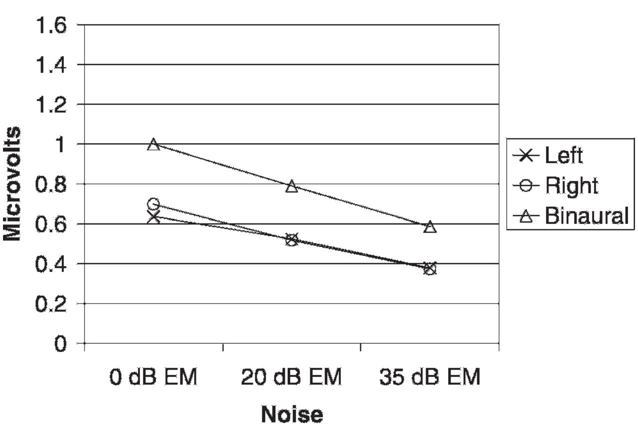

Figure 4. MLR-BE by ear and noise levels.

A significant BI effect was also found in the present study, with the summed monaural recordings being larger than the binaural recordings. For the ABR-BI, this effect was independent of noise level, and the degree of BI was equal in all noise conditions. For the MLR-BI, the difference between summed monaural and binaural recordings was dependent on noise level. Similar to the finding in the MLR-BE Ear × Noise interaction, the difference between summed monaural and binaural recordings was greater in 0 dB EM of noise than in 35 dB EM. Again, despite the significant differences noted, the degree of the effect sizes for the ABR and MLR interactions was similar even though the MLR interaction effect was numerically larger.

Taken as a whole, these findings have several implications for the acquisition of these potentials in normal hearing individuals. First, both monaural and binaural ABR and MLR potentials could be recorded for all subjects in white-noise levels as great as 35 dB EM. Although 40 dB EM of white noise was not used in the present study, pilot data using this level indicated that some subjects who did show

Table 6. MLR-BI Paired *t* tests for Ear × Noise Interaction

	0 EM Sum	20 EM Sum	35 EM Sum	0 EM Bi	20 EM Bi	35 EM Bi
0 EM Sum	–	*	*	*[a]	*	*
20 EM Sum	–	–	*		*[a]	*
35 EM Sum	–	–	–			*[a]
0 EM Bi	–	–	–	–	*	*
20 EM Bi	–	–	–	–	–	*
35 EM Bi	–	–	–	–	–	–

[a]Binaural interaction comparisons. Binaural enhancement refers to superior binaural hearing over monaural within a given noise level; a more complete explanation is provided in the introduction.

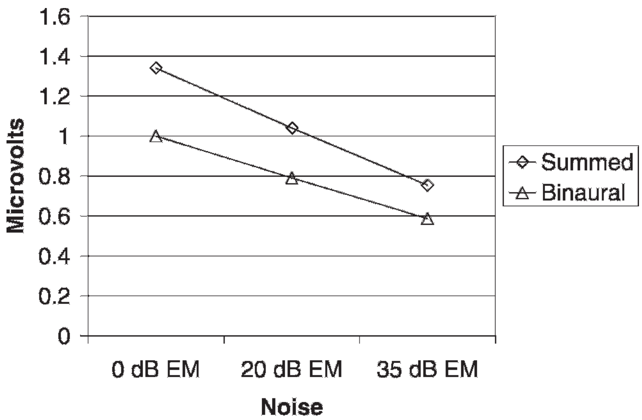

Figure 5. MLR-BI by ear and noise levels.

potentials in 35 dB EM did not show them when the noise was increased an additional 5 dB. The finding that 35 dB EM does yield recordable potentials speaks to the usability of this noise level in future studies, and it may also reflect an upper limit for the noise level in this paradigm.

Second, BE could be recorded in *both* the ABR and MLR in noise levels as great as 20 dB EM. However, in 35 dB EM of noise, BE is no longer present in the ABR. Therefore, if recording of BE in both potentials is desired, 20 dB EM would be suitable, whereas 35 dB EM would not. If an MLR-BE measure alone is the only recording of interest, then the noise level can be increased to 35 dB EM. Finally, BI can be recorded reliably in both the ABR and the MLR in up to 35 dB EM of noise. Although this effect becomes smaller for the MLR but not the ABR with increasing noise level, summed monaural peak amplitudes are still greater than binaural values at all noise levels for both potentials. Therefore, if recording of BI in both the ABR and MLR is desired, noise levels up to 35 dB EM could potentially be used.

Of additional interest in the present amplitude data is a phenomenon we have termed "binaural dominance" (BD). BD is a term used to describe a particular binaural-versus-monaural relationship across different noise levels. A noise level is binaurally dominant if its binaural evoked potential amplitude is significantly greater than monaural amplitudes in a lower noise level. The presence of BD indicates that a binaural advantage in higher levels of noise is maintained over monaural processing in lower levels of noise. Neural generators that demonstrate BD at a particular noise level may exhibit more efficient binaural processing than a neural generator that does not.

This BD phenomenon was witnessed in both the ABR-BE and MLR-BE recordings. In the ABR-BE measure, the 35 dB EM condition was binaurally dominant over the left- and right-ear monaural responses in 20 dB EM of noise. Therefore, when the noise level increased from 20 dB EM to 35 dB EM of white noise, the neural generators at the level of the ABR still yielded binaural evoked potential amplitudes that were greater than the monaural potentials obtained in less intense noise. In the MLR-BE measure, the 20 dB EM condition was binaurally dominant over the left-ear response in 0 dB EM of noise. No other conditions demonstrated BD in the ABR or MLR. It should be noted that these relationships of binaural dominance hold insofar as (a) equal processing can be assumed by a lack of statistical significance across conditions and (b) equal evoked potential amplitudes reflect an equal degree of stimulus processing.

The fact that BD was witnessed in the 35 dB EM condition of the ABR suggests that there may be some binaural benefits at this noise level, despite the absence of a significant difference between monaural and binaural recordings in 35 dB EM of noise. This argument is further strengthened by the finding that monaural amplitudes in 35 dB EM of noise did *not* differ from monaural amplitudes in 20 dB EM of noise. Therefore, even though BE disappears in 35 dB EM of noise in the ABR-BE, the presence of BD at this level suggests that some binaural advantages are still being maintained.

Latency Measures

Latency effects were noted in the present study only for wave V of the ABR. In this potential, there was a significant effect of noise so that as noise level increased, the latency of the wave shifted. This effect was on the order of 0.3 msec as the noise level was increased from 0 dB EM to 20 dB EM and 0.4 msec as it was increased from 20 dB EM to 35 dB EM. These shifts were larger than those reported by Burkard and Hecox (1983), Burkard and Sims (2002), and Gott and Hughes (1989), possibly because these previous studies used ipsilateral and not bilateral noise. However, despite the finding of a statistically significant difference for the latency of wave V across the three noise conditions, the magnitude of the difference in the present study was small. Consequently, this effect will not be considered further here.

ABR versus MLR—Tentative Physiological Differences

In the present study, a slightly different pattern of results was noted for BE and BI measures of the ABR and MLR when significance tests were considered. Although both the ABR-BE and MLR-BE measures showed significant interactions between Ear and Noise, the nature of this interaction differed across the two measures. As the noise level was increased to 35 dB EM, the MLR still showed significant BE, while the ABR-BE measure did not. Taken as a whole, these findings suggest that the MLR-BE measure may be a more robust measure of BE.

Differences between the ABR and MLR were also noted in the BI measure. For this measure, the ABR showed no interaction between Ear and Noise. Therefore, binaural benefits as measured by BI were equivalent across all noise levels. However, the MLR did demonstrate a significant interaction between these two variables. The interaction was such that as noise level increased, the difference between summed monaural and binaural amplitude measures tended to become smaller. This decrease in the difference between the summed monaural and binaural amplitude measures in greater levels of noise may indicate a decrease in the constituent monaural responses, an increase in the binaural response, or a combination of both. The present data do not allow for differentiation of these three scenarios.

The BE and BI differences noted earlier between the MLR and ABR imply two tentative conclusions regarding the physiology of binaural processing. The first is that the neural generators of the ABR and the MLR that are involved in binaural processing may respond differently to increasing levels of noise. The second is that, because the relationship between ABR and MLR varied depending on which binaural measure was examined, the respective mechanisms underlying BE and BI and/or of noise suppression may be somewhat different. Although they are not likely to be completely unrelated, each may represent a different way of looking at how the CANS deals with binaural processing of sound. It should be noted that, because effect-size statistics did not indicate as much of a difference between ABR and MLR binaural processing, these conclusions are tentative until replicated.

In regards to physiology, research has been conducted in humans concerning what neural events underlie the generation of binaurally evoked potentials. Pratt et al (1998) reported ABR BIC results for patients with small, localized pontine lesions. Their results showed (a) that a BIC wave occurring in the vicinity of wave IV tended to be related to the integrity of the ventral–caudal trapezoid body, (b) that the BIC wave occurring in the vicinity of wave V tended to be related to the integrity of the ventral trapezoid body, and (c) that the BIC wave occurring in the vicinity of wave VI tended to be related to the integrity of the rostral lateral lemniscus. These results expand on the well-known finding that the superior olivary complex (SOC) and related structures are critical in binaural processing (Galambos et al, 1959) but don't yield much information that aids in the interpretation of the present BE and BI phenomenon. In animal models, it has been shown that 80% of the neurons in the CANS respond to stimulation of either ear and that some of these neurons exhibit an inhibitory influence when activated contralaterally (Moore, 1991; Ungan and Yagcioglu, 2002). There exists, then, the possibility that binaural processing plays some important inhibitory role (Galambos et al; McPherson and Starr, 1993).

A potential physiologic difference between the neural generators of the ABR and MLR may arise from the auditory efferent system. It is known that this efferent system can suppress neural activity when the auditory system is exposed to noise (Liberman, 1988, 1989). Additionally, the efferent system may be divided physiologically into two distinct systems: (a) a caudal system that includes connections between the SOC and the cochlea (i.e., the olivocochlear bundle; Warr, 1980), and (b) a system that is more rostral and includes connections between the auditory cortex and the SOC (Spangler and Warr, 1991). Given that the efferent system is stimulated by noise and that the neural generators for the ABR and MLR may be located in different regions of this system, differences between these two potentials witnessed in the present study may be related to differences in efferent activity.

Comparisons to Past Studies

Binaural effects witnessed in the ABR and MLR quiet conditions were compared to findings in previous research. These comparisons were made to the quiet condition only because this condition was most similar methodologically to previous studies. For the ABR-BE measure, the present study noted a 0.5 microvolt increase in wave V amplitude when stimuli were presented binaurally instead of monaurally. This increase was nearly identical to the binaural amplitude increase of 0.3 reported by Ainslie and Boston (1980) but is slightly larger than the 0.1 microvolt increase at 65 dB SL reported by Starr and Achor (1975). Despite these slight discrepancies, all three amplitude changes are of the same general magnitude.

For the ABR-BI, the present study found a 0.18 microvolt increase in the summed monaural over the binaural response. This increase is similar to the 0.2 microvolt increase reported in BIC measurements by Dobie and Norton (1980). Additionally, when an average BIC ratio is computed using the present data in a manner similar to that used by Debruyne (1984; i.e., Quiet Binaural [1.22]/Quiet Summed Monaural [1.4]), the value obtained for these data (0.87) is similar to that reported by Debruyne (0.83).

For the MLR-BE, the present study found a 0.3 microvolt increase in Na–Pa amplitude during binaural recordings. This finding represents an approximate 50% increase in amplitude when compared to the monaural recordings. This amplitude change is similar to that reported by Versino et al (1991), Seki et al (1993), and Baez-Martin and Cabrera-Abreu (2000), who reported

0.15, 0.2, and 0.2 microvolt increases, respectively. However, the percentage increase in the binaural recordings reported in the present study was larger than that reported by Woods and Clayworth (1985), who noted only a 20% increase. Discrepancies may arise from a difference in the way amplitude was calculated across the two studies. For the MLR-BI measure, the present study found that summed monaural responses were greater than the binaural responses by 0.3 microvolts. On the one hand, Dobie and Norton (1980) reported a much larger BIC effect that was on the order of 1.5 microvolts. This difference may arise from variation in the locations of the reference electrodes across the two studies. Dobie and Norton used earlobe references for the MLR, whereas the present study used the nape of the neck. On the other hand, the present results do compare well to Debruyne (1984). When an average BIC ratio is computed using the present data (i.e., Quiet B/Quiet Summed Monaural [1.26]), the value obtained for these data (0.73) is similar to that reported by Debruyne (0.787).

Noise effects witnessed in ABR and MLR were also compared to those in previous research. To make comparisons that were similar methodologically to past research, the authors used only the right-ear values from the present study. Binaural values were not used because previous research tended to limit stimulus presentations to one ear. Additionally, because left- and right-ear values were similar statistically, using either one for comparison was considered to be sufficient for the present comparisons.

For the ABR measure, a 0.28 microvolt decrease was noted in wave V amplitude as the noise was increased from 0 to 20 dB EM, a 0.09 microvolt decrease was noted with increases from 20 to 35 dB EM, and a 0.37 microvolt decrease was noted with increases from 0 to 35 dB EM. This trend is similar to that found by Burkard and Hecox (1983), who reported a 0.5 microvolt decrease from 0 to 20 dB EM, a 0.1 microvolt decrease from 20 to 40 dB EM, and a 0.6 decrease from 0 to 40 dB EM. However, this finding is less similar to the findings of Gott and Hughes (1989), who reported no microvolt change from 0 to 20 dB SL and a 0.16 microvolt from either of those conditions to 40 dB SL.

For the MLR measure, a 0.15 microvolt decrease was noted as the noise was increased from 0 to 20 dB EM, a 0.16 microvolt decrease was noted from 20 to 35 dB EM, and a 0.31 microvolt decrease was noted from 0 to 35 dB EM. The change from 0 to 35 dB EM can be compared to the change from 0 to 24 dB signal-to-noise ratio reported by Smith and Goldstein (1973). Their value, approximately 0.04 microvolts, is much lower than the value reported in the present study. Discrepancies may arise from the fact that the dB SPL of their noise level in the poorer signal-to-noise ratio condition was likely lower than that used in the present study. They report their masking as being 24 dB below the level that just masked a 24 dB SL click, whereas the present study presented clicks at 60 dB SL and noise in the poorest signal-to-noise ratio condition at 35 dB EM. Additionally, Smith and Goldstein used only ipsilateral noise, whereas the present study presented noise in the sound field.

Results from Gott and Hughes (1989) also differed from those of the present study. They reported no effect on MLR Pa amplitude with increasing noise level. This finding may be a result of a difference across studies in the way in which amplitude was calculated. In the quiet condition, Gott and Hughes reported Pa amplitudes that were much smaller than those witnessed in the present study, despite similar filters being used in both cases. Additionally, Gott and Hughes also used ipsilateral noise, which differs from the bilateral noise presentation in the present study.

Clinical Implications—Future Research and Limitations

The present study represents the first step in establishing a new electrophysiological measure of binaural hearing in noise. It was found that both monaurally and binaurally evoked ABR and MLR potentials could be recorded in up to 35 dB EM of noise using either the BE or BI measure in normal hearing individuals. In future research, the same protocol must be applied to a population with (C)APD of known etiology who report difficulties hearing in noise to fully validate this procedure as a clinical tool. It would be expected that this group would differ from normal listeners in at least the 35 dB EM condition, which places the greatest demands on the CANS.

It should be noted, however, that one potential strength of this protocol may be its ability to diagnose pathology in cases of *ambiguous* auditory function—that is, patients who would normally pass auditory tests of peripheral and central function but still report tremendous difficulties hearing in noise. One population of interest might be patients with King-Kopetzky Syndrome (KKS). KKS is a diagnosis given to a combination of auditory and nonauditory symptoms, including difficulties hearing in noise despite relatively normal peripheral hearing and a large stress reaction to these auditory symptoms (Zhao and Stephens, 1996). Research has shown that patients with KKS are more likely than normal controls to have a history of OM and a family history of hearing loss (Stephens et al, 2003). The present protocol might be revealing in these cases.

This protocol offers several additional advantages in clinical application. Presentation of noise in the sound field is a more externally valid method of measurement. Additionally, computation of the BI as the sum of the two monaural peak values allows the audiologist to use this protocol even if the physiologic averager cannot present bilateral noise or compute BIC waves. Additionally, once clinical data have been obtained, the protocol can be streamlined to include only a single noise level, thereby decreasing the amount of time it takes to complete the test. Finally, acquisition of both the ABR and MLR simultaneously may aid in site-of-lesion analysis, although what comprises BE and BI will need to be more clearly understood before such comparisons can be useful.

Although the present study does represent a first attempt toward establishing a new clinical measure, its results can be generalized only to a normal hearing, young adult population such as that used in the present study. Research has shown a variety of maturational effects on electrophysiological measures of binaural processing. McPherson et al (1989) showed that the amplitudes of the BIC peaks were smaller at Na and larger at Pa in adults relative to infants. Additionally, Kelly-Ballweber et al (1984) showed a reduction in amplitude of the binaural potentials relative to the summed monaural in a young adult population but not in an older adult population. Therefore, these age-dependent changes in the BIC need to be investigated further before these results can be generalized to adolescents or the older adult population.

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NOTES

1. For all ANOVAs, (a) Huynh-Feldt adjusted degrees of freedoms were used for all repeated measures ANOVAs to control for any potential violations of the sphericity assumption (Max and Onghena, 1999), (b) ω^2 values were the generalized form of the statistics, and (c) the alpha level of .05 for all post hoc paired *t* tests was transformed using a Bonferroni adjustment.

2. All mean trends discussed refer to values from the main effects analysis unless otherwise specified.

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