Perception of Auditory Movement in Children with Poor Listening Skills: An ERP Study

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Abstract

Long-latency ERP components were examined for scalp activation differences in children with poor and good listening skills in response to auditory movement created by IIDs. Eighteen children were grouped based on a parent questionnaire (CHAPS; Smoski et al., 1998) and clinical evaluation by a licensed audiologist. Obligatory cortical responses were recorded to an auditory movement and an auditory control task. Results showed greatest activation at fronto-central electrode sites. P1, N1, and P2 showed no significant effects. Significant differences in N2 amplitude and latency were present between groups at the lateral electrode sites (FC3, FC4) in the auditory movement but not in the auditory control task. More specifically, good listeners exhibited predominance of activation over the right hemisphere for left-moving sounds, whereas the poor listeners exhibited symmetric activation. These results suggest that abnormal hemispheric activation may be one of the reasons behind poor listening skills observed in some school-aged children.

Key Words: Auditory perceptual disorders, child, evoked potentials, sound localization

Abbreviations: CHAPS = Children’s Auditory Performance Scale; EEG = electroencephalographic; ERP = event-related potentials; IID = interaural intensity differences; ITD = interaural timing differences; N1 = negative peak between 80–120 milliseconds; N2 = negative peak between 180–290 milliseconds; P1 = positive peak between 50–90 milliseconds; P2 = positive peak between 140–190 milliseconds; P3 = positive peak at 300 milliseconds or later; VEOG = vertical electro-oculographic

Sumario

Se examinaron los componentes de los ERP de latencia prolongada, buscando diferencias de activación en el cráneo, en niños con habilidades auditivas buenas y malas, en respuesta a movimientos auditivos creados por diferencias interaurales de intensidad (IID). Se agruparon dieciocho niños de acuerdo a un cuestionario llenado por los padres (CHAPS; Smoski y col., 1998) y a una evaluación clínica realizada por un audiólogo certificado. Se registraron respuestas corticales obligatorias ante un movimiento auditivo y una tarea de control auditivo. Los resultados mostraron una activación mayor en los sitios de colocación de electrodos fronto-centrales. P1, N1 y P2 no mostraron efectos significativos. Se presentaron diferencias significativas entre grupos en la amplitud y la latencia del N2, con el sitio de electrodo lateral (FC3 y FC4), ante el movimiento auditivo pero no ante la tarea de control auditivo. Más específicamente, los sujetos con buena audición exhibieron predominancia en la activación en el hemisferio derecho, para sonidos moviéndose a la izquierda, mientras que aquellos con pobre audición exhibieron una activación simétrica.
According to the American Speech-Language Hearing Association (1996), auditory processing involves mechanisms responsible for sound localization and lateralization, auditory discrimination, auditory pattern recognition, temporal aspects of audition, auditory performance with competing acoustic signals, and auditory performance with degraded signals. This definition has given focus to research and clinical diagnosis of auditory processing disorders (APD; Jerger and Musiek, 2000; Bellis, 2003) and has resulted in a better understanding of the behavioral and underlying neurological differences in children with APD (Estes et al, 2002; Purdy et al, 2002; Warrier et al, 2004). There continues to be a lack of research examining spatial localization and perception of sound movement in children with problems processing auditory information. Bellis (2003) states that there is a need for more effective tests of localization and lateralization in this population. The goal of this study was to objectively investigate the neural processing of sound movement in children with poor listening skills. For the purpose of this study, poor listeners are defined as children with (1) poor auditory performance in daily life as reported by parents on the Children’s Auditory Performance Scale (CHAPS; Smoski et al, 1998) and (2) a clinical diagnosis of APD obtained by a certified audiologist based on an auditory processing test battery.

Behavioral studies indicate that sound localization is based on the processing of binaural cues from interaural time and level differences and of monaural spectral cues from the filtering effects of the pinna, head, and body (Palmer, 1995). The ability to understand speech in noise and to localize sound sources (i.e., complex auditory processing) depends in large part on the ability to use the binaural information in signals with spatial information (e.g., Durlach and Colburn, 1978). Although there is a solid research tradition in the behavioral measurement of basic and complex binaural tasks (e.g., Durlach and Colburn, 1978; Hauser et al, 1983; Koehnke et al, 1995; Koehnke and Besing, 2001), the application of research on binaural processing to auditory event-related potentials (ERPs) has been less extensive.

The initial coding of the binaural cues of interaural phase and intensity differences, which are used in sound localization, occurs at the level of the superior olivary nuclei (Casseday and Neff, 1975; Polyakov and Pratt, 1996; Pratt and Polyakov, 1999). However, the perception of the spatial location of sound occurs at a higher level within the central auditory system (Itoh et al, 2000). Higher level processing of binaural information is illustrated by sensitivity of the primary and secondary auditory cortex to interaural phase or intensity differences in single cell recordings in mammals (Pickles, 1988; Mendelson and Grasse, 2000; Xu et al, 2000) and the measurement of ERP responses to binaural cues in humans (Ungan et al,
For example, the N1 waveform in adults has been used to study the neural processing of interaural time (ITD) and interaural intensity (IID) differences in a train of click stimuli (Ungan et al, 2001). Dipole analysis of the N1 obtained in the Ungan et al’s study indicated contralateral primary cortex dominance in response to both binaural cues, specifically in the supratemporal plane. Several studies have used dipole source localization and neuroimaging techniques to determine how binaural features are represented in the human brain (Griffiths et al, 1994; Mäkelä and McEvoy, 1996; Pavani et al, 2000). These studies have confirmed two response patterns to sound movement: (1) greater activation in the hemisphere contralateral to the direction of the sound movement/localization (e.g., greater activation of the right hemisphere for left moving sounds), also referred to as contralateral activation (Mäkelä and McEvoy, 1996; Pavani et al, 2002), and (2) overall more pronounced activation in the right hemisphere when compared to nonspatial stimuli, regardless of the direction of sound movement (Griffiths et al, 1994; Anourova et al, 2001; Xiang et al, 2002).

Many auditory perceptual skills have extended maturation time courses, such as auditory gap detection (Phillips, 1999), temporal ordering (Irwin et al, 1985), dichotic listening (Jerger et al, 2002), and sound localization (Besing and Koehnke, 1995; Litovsky, 1997). In general, neuromaturation of sound processing can be seen in the age-related changes in the obligatory components of auditory ERPs (Ponton et al, 1996, 2000; Sharma et al, 1997; Čeponienė et al, 2002). The term “obligatory components” refers to components in the ERP waveform that are elicited and vary in response to stimulus characteristics.

Although binaural cues in adults have been shown to affect the obligatory N1 component (Ungan et al, 2001), in young children P1 and N2 (sometimes referred to as N1b; e.g., Sharma et al, 1997) dominate the long-latency obligatory auditory ERPs. According to Ponton et al (1996, 2000), N2 experiences a more complex maturation pattern than the earlier responses. N2 latency is significantly shorter in younger subjects until age 14 (electrodes C3, C4, and Cz); these shorter latencies continue at electrode C4 until adulthood (age 18–20). These latency changes are not evident at the Fz electrode (Ponton et al, 2000). In addition, N2 demonstrates an interhemispheric latency difference that increases with age; longer latency over the hemisphere contralateral to the stimulated ear (only the left ear was stimulated in their study) is most notable in adulthood. N2 amplitude increases until age ten and then decreases in amplitude until adulthood. Maturational changes were also discussed in Čeponienė et al (2002), with their obligatory responses showing the greatest activation at the fronto-central scalp sites.

Several researchers have suggested that the generator sources for N1 and N2 are not located in the same area of the cortex and represent different aspects of auditory processing (Čeponienė et al, 2002; Takeshita et al, 2002). In children, N2 appears to be tightly coupled to stimulus complexity level (Čeponienė et al, 2001). Thus, children with problems processing auditory information may manifest with differences in ERP responses (N1 vs. N2) that are dependent on the stimuli used and the cause of the processing problem (language impairment, auditory processing disorders, and/or dyslexia).

In a series of articles by Kraus and colleagues, late evoked potentials in response to speech stimuli have demonstrated processing differences in children with learning problems when compared to children without learning problems (Cunningham et al, 2000; King et al, 2002; Warrier et al, 2004; Wible et al, 2002). Cunningham et al (2000) found that, in addition to maturational changes occurring in P1/N1/N2, behavioral measures of auditory processing have a predictive relationship with the latency of the N2 component. While Kraus et al’s findings have demonstrated no differences in the overall development of P1/N1/N2 to speech sounds presented in quiet between children with and without learning problems, differences have been obtained for speech sounds in noise (King et al, 2002). When the P1/N1/P2/N2 components generated in quiet and in background noise are correlated, children with learning problems have a reduction in the mean correlation (King et al, 2002; Wible et al, 2002). The technique of cross-correlation within individual subjects demonstrates a highly degraded response in the presence of noise, particularly in the N2 region, in listeners with learning problems (Warrier et al, 2004). This poor correlation
appears to be a result of a reduced N2 latency in the learning-impaired children in the presence of noise. The authors suggest that the N2 latency differences in these children with learning problems may be due to auditory processing deficits (Warrier et al., 2004). Current research from this group is focusing on the effect of auditory-based training on the response correlation in the N2 region in children with learning problems (Warrier et al., 2004). The success of this training suggests that these children have an underlying neurophysiologic problem within the auditory system.

Purdy et al. (2002) have also demonstrated differences in the N2 component in children with learning disabilities and a “possible APD” (Purdy et al., 2002, p. 370). They looked at the obligatory components in response to simple pure-tone stimuli presented in an oddball paradigm to children with possible APD as diagnosed by a psychologist, and to children with no learning or hearing problems as reported by their parents. Children were identified as possibly having APD based on their performance on measures of auditory immediate memory/attention, auditory and visual immediate memory/attention, auditory long-term memory/attention, and auditory discrimination of speech phonemes. In addition to larger peak-to-peak amplitude of P2-N2, shorter latencies and smaller amplitudes were observed for the earlier peaks, P1 and N1, in the children with processing problems. The authors concluded that the differences in ERP results between the two groups of children might account for the difficulties experienced by the children with possible APD.

Differences in the amplitudes of the obligatory components between children suspected of an auditory processing disorder and children not suspected of an auditory processing disorder were also found by Liasis et al. (2003). Children were suspected of APD based on self-report and parental report, normal audiometric results, abnormal scores on a screening test for APD, no CNS pathology, and normal scores on measures of speech and language or cognitive abilities. Liasis et al. recorded auditory event-related potentials to phonemes presented in an oddball paradigm and reported larger peak-to-peak P1-N1 and P2-N2 amplitudes and smaller absolute amplitudes for N1 and P2 in children suspected of auditory processing disorders as compared to controls. The apparent discrepancies between these two studies (Purdy et al., 2002; Liasis et al., 2003) may be due to stimulus differences, differences in the definition of the subject population or in ERP measures utilized.

The only known study to date that examines moving sound stimuli in children with auditory processing problems is from Jerger and colleagues (Estes et al., 2002). Jerger and Estes (2002) introduced a moving sound stimulus paradigm and measured the electrophysiological response in children (9–12), younger adults (18–34), and older adults (65–80). They found that the P3 component (between 400 and 800 msec) to sound movement evoked a robust response in normal children with a greater activation over the right hemisphere than over the left. Children showed a substantially larger asymmetry than either the seniors or the young adults. When this same stimulus paradigm was applied to children who are poor listeners (Estes et al., 2002), ERP responses in the midline region were similar between good and poor listeners; however, there were group differences for the lateral electrodes. Normal listeners had a larger activation to the right while poor listeners had a smaller asymmetric activation to the left; differences in hemispheric activation patterns were only analyzed for the P3 component. This suggests that the poor listeners are lacking the right hemisphere specialization for sound movement found in the adult literature (Griffiths et al., 1994; Anourova et al., 2001; Xiang et al., 2002) and in normal children (Estes et al., 2002; Jerger and Estes, 2002).

In contrast to Estes et al., who evaluated group effects of sound movement in the P3 component, the current investigation determines whether the obligatory ERP components in response to sound movement distinguish between children who are poor listeners and children who are good listeners. Based on previous research findings, perception of sound movement should result in (1) greater amplitudes in the hemisphere contralateral to the direction of the sound movement and (2) overall greater amplitudes in the right hemisphere for the good listeners, while the poor listeners would exhibit less hemispheric specialization in the form of symmetrical bilateral activation patterns. This study focuses on the neural processing of IIDs, creating an illusion of sound
movement. Since auditory gap detection does not rely on the processing of binaural intensity cues, a gap detection task was included in the current study as a control condition.

METHODS

Subjects

Eighteen children (ten females, eight males; mean age 9.61, SD 1.65; age range 7–13 years) participated in the study. Participants were recruited from the Department of Audiology at JFK Johnson Rehabilitation Institute or by advertisement. Participants were only included if the scores obtained from the Children’s Auditory Performance Scale (CHAPS; Smoski et al, 1998), answered by the parents, corroborated with results on an auditory processing test battery administered by a licensed audiologist (see Table 1). The CHAPS is a behavioral questionnaire that is effective in defining and evaluating listening behaviors that may generate a referral for Central Auditory Processing testing (Bellis, 2003). The CHAPS includes questions specifically addressing listening abilities involved in the perception of auditory movement, such as the detection and processing of multiple auditory inputs. When the questionnaire was field tested in children with and without auditory processing deficits, clear differences were obtained between the groups with no overlap in the range of scores for each group (Smoski et al, 1998).

Nine children (five males, four females; mean age 9.89, SD 1.69) were identified as poor listeners in this study based on an at-risk score on the CHAPS (total condition score between -12 and -130) and abnormal performance in the APD test battery on at least two tests measuring the same auditory process (Table 1). As abnormal scores across all three auditory processes would point towards a global disorder (e.g., attention deficit, mental disability), we ascertained that none of the poor listeners had abnormal performance on multiple tests in all of the processes tested. Nine children (three males, six females; mean age 9.33, SD 1.66) obtained a passing score on the CHAPS (total condition score between +36 and -11) and had normal performance in all or all but one task per auditory process on the APD test battery; they will be referred to as good listeners in this study. All participants were right-handed based on a handedness questionnaire (Annett, 1970) and had normal hearing as measured by an audiometric screening at octave intervals between 500 and 4000 Hz (threshold ≤25 dB HL).

Stimuli

Two auditory tasks were employed in the current study, auditory movement detection and auditory gap detection. The auditory gap detection task was included as a control task because it does not require integration of auditory cues from both ears. In both tasks, the standard stimulus was a 500 msec burst of broadband noise presented binaurally at 60 dB SPL. The tasks differed in the target stimuli that were to be identified. In the auditory movement task, participants were to detect noise bursts that appeared to be moving from the median plane to the left or to the right. The illusionary sound movement was solely created by IIDs (Figure 1, adapted from Estes et al, 2002). In the auditory gap task, participants were to identify silent gaps in the center of the noise burst. The duration of the gap was either 30 or 100 msec, and the overall length of the stimulus remained constant at 500 msec across conditions (Figure 1). All stimuli were presented with an interstimulus interval of 2 seconds. The level of the IIDs and the gap

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<tr>
<th>Auditory Process</th>
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<td>SSW Staggered Spondaic Word Test</td>
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<td>Temporal Ordering</td>
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length in this study were selected to ensure high accuracy scores in both poor and good listeners. This allowed us to evaluate group differences in neurophysiological processing of stimuli when the behavioral performance is not compromised. A detailed description of the auditory stimuli and paradigm can be found in Estes et al (2002).

**Experimental Procedure**

Participants were seated in a comfortable chair and stimuli were delivered to participants through earphones (left, right). A response panel was placed in front of the participant. The participant’s task was to push the button upon each target presentation. A standard oddball paradigm was employed, with standard stimuli occurring in 50% of trials (100 trials) and the two types of target stimuli in 25% of trials (50 trials each).

**EEG Recordings**

Brain electrical activity was recorded using the Neuroscan system. An elastic cap (Neurosoft), equipped with 32 silver-silver chloride electrodes according to the International 10–20 system was affixed to the participant’s scalp. Vertical and lateral electro-oculographic activity (VEOG) was monitored by placing electrodes above and at the outer canthus of the left eye. During recording, linked mastoid electrodes served as reference electrodes, and APZ served as the ground electrode. Impedances for each electrode did not exceed 5 kohm as measured before the test session.

Electroencephalographic activity was amplified and bandpass, analog filtered from .15 to 50 Hz (-12 dB per octave). Digitization was then carried out through Neuroscan Acquisition. Digitized individual sweeps of the electroencephalographic (EEG) activity were recorded and stored for off-line analysis, averaging, and digital filtering.

Auditory evoked potentials were recorded at a sampling rate of 1000 Hz. Sweep duration extended from -200 to +1400 msec relative to stimulus onset. A prestimulus baseline average was calculated based on the first 200 data points (first 200 msec). Off-line signal averaging was carried out after off-line

![Waveforms](image_url)

**Figure 1.** Waveforms of auditory movement and auditory gap stimuli. Signal is broadband noise with duration of 500 msec. In the auditory movement task, the amplitude levels in both channels are equal at onset but differ by 18 dB at offset (adapted with permission from Estes et al, 2002).
**Figure 2.** Spatial movement detection. Grand averaged waveforms across subject groups and movement conditions for poor and good listeners.

**Figure 3.** Auditory gap detection. Grand averaged waveforms across subject groups and gap conditions for poor and good listeners.
artifact rejection and baseline correction procedures. Individual sweeps were rejected when the electro-oculographic activity (VEOG) exceeded ±50 microvolts (µV). The mean number of accepted epochs was 30 for each auditory movement condition, and 33 for each auditory gap condition. Upon completion of the previous steps, the averaged waveforms were linearly detrended, low-pass digitally filtered at 20 Hz with a filter slope of -48 dB per octave and re-referenced to a common averaged reference.

Statistical Analysis

Latency and amplitude measures were obtained with a software package (Neuroscan Edit 4.3) that identified both measures in the P1, N1, P2, and N2 peaks of the individual averaged waveforms in response to target stimuli. In agreement with previous findings (Ceponiene et al., 2002), the children’s obligatory components were chiefly located at the fronto-central electrode sites. Therefore, the latency window for peak identification was based on visual inspection of the grand averaged waveforms across conditions and subject groups at FCZ (Figures 2 and 3). The latency windows were 50–90 msec for P1, 80–120 msec for N1, 140–190 msec for P2, and 180–290 msec for the N2 component. Peak identification was based on the point of largest amplitude within the predetermined latency window.

Separate repeated measures ANOVAs were conducted for the auditory movement and auditory gap tasks. Within-subject independent variables included condition (auditory movement: movement direction left or right; auditory gap: gap duration 30 or 100 msec) and hemisphere (left, FC3; right, FC4).

Subject group was included as a between-subject independent variable. We were ultimately interested in the differences in brain activation patterns between good and poor listeners in response to sound movement. Therefore, we will report the results of the auditory gap detection task only in reference to the results of the auditory movement task.

RESULTS

Behavioral Results

Based on the accuracy scores, all subjects performed well above chance-levels (>65%). Separate repeated measures ANOVAs of percent correct scores for the auditory movement and auditory gap tasks with stimulus type (standard, target) as the within-subject variable and subject group as the between-subject variable revealed no significant effects of group (F [1,16] = 3.250; p = .090), stimulus type (F [1,16] = .855; p = .369), or stimulus type by group (F [1,16] = 1.858; p = .226).

Grand Averaged Waveforms

For auditory movement as well as auditory gap detection, the earliest peaks observed reliably in the grand averaged waveform across subject groups and conditions were the obligatory P1, N1, P2, and N2 components (from 50 to 290 msec), followed by a significantly later endogenous P3 component between 350 and 800 msec (Figures 2 and 3). It is important to note that the obligatory components did not overlap in time with the endogenous P3 component. The goal of the current paper was to evaluate group differences for only the obligatory components.

ERP Analyses

Analyses of the amplitude and latency of the P1, N1, and P2 peaks did not show significant findings for auditory movement in the lateral fronto-central electrode sites (FC3, FC4). Analyses of the N2 component are reported below.
**Auditory Movement Detection**

**N2 Amplitude at FC3 and FC4**

Significant interaction effects of movement by hemisphere (F[1,16] = 5.138; p = .038) and of group by movement (F[1,16] = 7.580; p = .014) were found for the auditory movement task. Post hoc paired samples t-tests for the movement by hemisphere interaction resulted in a significant effect of hemisphere for sound movement to the left (t = 3.109, df = 17, p = .006) but not to the right; that is, when groups were combined, greater activation was observed for left movement over FC4 as compared to FC3; no hemispheric differences were obtained for right movement (Figure 4). Post hoc paired samples t-tests for the group by movement interaction revealed that N2 amplitude in the good listeners was greater for left movement than for right movement (t = -2.772, df = 8, p = .024); no significant difference between left and right movement was found in the poor listeners. Furthermore, independent samples t-tests showed that N2 amplitude in response to left movement was significantly greater in the good listeners as compared to the poor listeners (t = -2.384, df = 16, p = .030; Figure 5). No significant findings were obtained for N2 amplitude in response to right movement. As the observed effects were mainly caused by differences in response to left-moving sounds, repeated measures ANOVAs were conducted including only the left movement, with hemisphere as the within-subject variable and subject group as the between-subject variable. Main effects of hemisphere (F[1,16] = 9.475; p = .007) and of group (F[1,16] = 5.684; p = .030) were obtained. Subsequent paired samples t-tests for each subject group showed that in good listeners the N2 amplitude was greater at FC4 than at FC3 (t = 2.654, df = 8, p = .024; Figure 6) while no significant difference between hemispheres was observed in the poor listeners in response to left moving sounds. Finally, separate independent samples t-tests for each hemisphere showed a significant difference between groups at FC4 (t = -2.492, df = 16, p = .024; Figure 6).

**N2 Latency at FC3 and FC4**

Repeated measures ANOVA with N2 latency as the dependent variable revealed a significant interaction effect of hemisphere by group (F[1,16] = 4.712, p = .045). Post hoc paired samples t-tests for each subject group showed good listeners to have shorter N2 latencies over FC3 than FC4 (t = 3.313, df = 8, p = .011). N2 latencies over FC3 and FC4 did not differ significantly in poor listeners. As sound movement did not contribute to the observed interaction effect, the grand averaged waveforms in Figure 7 represent responses averaged across left and right moving sounds. As stated earlier, N2 peaked earlier over FC3 than FC4. Interestingly, at the FC3 peak latency, the N2 amplitude was observed to be equal over FC3 and FC4. However, an additional negative shift was observed at the FC4 scalp site with a peak

![Figure 5](image1.png) Interaction effect of group by movement showing that in good listeners sounds moving to the left hemisfield evoked greater responses than sounds moving to the right hemisfield. Furthermore, for sounds moving to the left hemisfield, good listeners had greater N2 amplitude than poor listeners. *Significant at p = .030. **Significant at p = .024.

![Figure 6](image2.png) Repeated measures ANOVA for left movement only. In good listeners, the N2 amplitude was greater over FC4 than FC3. N2 amplitude at FC4 was greater for good listeners than poor listeners. *Significant at p = .029. **Significant at p = .024.
latency occurring around 280 msec post stimulus onset. We will refer to this additional negative shift as the N2' for the remainder of the paper. The N2' was not present in the grand averaged waveform of the poor listeners.

**N2 Amplitude and Latency at FCZ**

To ascertain that the observed effects truly represented differences in scalp activation patterns for auditory movement and were not a mere reflection of overall ERP differences between subject groups, we conducted separate repeated measures ANOVAs for N2 amplitude and latency at midline electrode FCZ. No significant differences between groups were found.

**Auditory Gap Detection**

In contrast to the movement task, no significant group differences were obtained in the statistical analyses of N2 amplitude and latency at FC3, FC4, and FCZ for the auditory control task.

**SUMMARY**

Left-moving sounds evoked a clear hemispheric asymmetry in good listeners, by way of greater N2 amplitude at FC4.
compared to FC3, while no hemispheric differences were found in poor listeners. Furthermore, N2 amplitude at FC4 for left-moving sounds was greater in good listeners than in poor listeners. The hemispheric asymmetry in good listeners was accompanied by longer latencies at FC4 than at FC3 regardless of the direction of the sound movement; this may be due to an additional negative shift at FC4, which we have labeled “N2′.” N2′ was absent in the poor listeners. Finally, the corresponding main effects and interaction effects in the auditory control task were not significant.

**DISCUSSION**

The current study adds to the literature of auditory processing disorders in that few studies have investigated obligatory ERP components for sound movement in children with poor listening skills. In addition to the detection of sound movement, children were asked to perform an auditory gap detection task (control task), which involved stationary sound images. ERP measures revealed group differences in the auditory movement task that were not noted in the auditory gap detection task, nor in the behavioral measures of auditory movement detection. The goal of this study was to evaluate group differences related to the processing of sound movement in the horizontal plane. Therefore, we will focus our discussion on the pattern of results unique to sound movement distinguishing poor listeners from good listeners.

The overall impression of the present findings is that scalp activation patterns for sound movement differed statistically between good and poor listeners in that asymmetry in scalp activation was present in good listeners but absent in poor listeners. Poor listeners did not have greater difficulty than the good listeners with the tasks at hand; statistical analysis of the behavioral accuracy scores showed no group differences. This indicates that the ERPs obtained in this study reflect underlying neurophysiological differences when behavioral performance is not compromised. In addition, no group differences were obtained in the analysis of the N2 amplitude and latency measures at midline electrode FCZ, suggesting that our results truly represent different scalp activation patterns for poor listeners and good listeners.

In the good listeners, sounds moving from the median plane horizontally to the left hemifield evoked greater N2 amplitude over the right hemisphere (over FC4) as compared to the left hemisphere (over FC3). Although we did not conduct source analyses of the ERP activation patterns in the current study, source localization studies and MEG studies to auditory movement and localization have established that the contralateral, and not the ipsilateral, auditory pathway processes sound movement (Palomäki et al, 2000; Ungan et al, 2001; Fujiki et al, 2002). According to Ungan et al (2001), this was found to be particularly true for sound stimuli in which the illusionary motion was created by IIDs, as was the case in our study. Mäkelä and McEvoy (1996) also utilized IID stimuli to create a perception of sound motion. Utilizing MEG as a recording technique in young adults, they registered greater N1m amplitudes in the hemisphere contralateral to the ear receiving the intensity increase. Similarly, a greater N1m response was found contralateral to the location of stationary sound images created with head-related transfer functions (Palomäki et al, 2000).

In addition to contralateral activation patterns for sound perception, predominance of the right hemisphere for spatial hearing has been documented in behavioral and neuroimaging studies. Greater localization accuracy has been reported for sounds presented in the left hemifield as compared to the right hemifield (Burke et al, 1994). Over and above the greater activation in the hemisphere contralateral to the locus of sounds, Palomäki et al (2000) reported overall greater amplitude in the electromagnetic field responses (EMFs) of the right hemisphere than the left hemisphere and attributed this difference to the specialized function of the right hemisphere for spatial organization of auditory events. Thus, in contrast to sounds moving to the right hemifield, sounds moving to the left hemifield are more likely to evoke greater activation over the right hemisphere, not only because the right hemisphere is specialized for sound movement but also because the hemisphere contralateral to the sound movement (i.e., the right hemisphere for left-moving sounds) is specifically involved in processing of the auditory information. Similarly, for right-moving sounds, right hemisphere specialization for sound movement in
combination with contralateral activation (i.e., the left hemisphere for right-moving sounds) could result in bilateral activation. Indeed, in the current study, the asymmetry in N2 scalp activation observed in response to left-moving sounds is lacking in response to right-moving sounds. Instead, we documented a bilateral activation pattern for sounds moving to the right (Figure 4).

As high resolution EEG is needed for accurate source localization, we cannot infer that the neural sources evoking right scalp activation patterns originated in the right hemisphere. However, there is evidence from evoked magnetic field recordings (Xiang et al., 2002; Mathiak et al., 2003) as well as evoked potential recordings in adults (Ducommun et al., 2002) suggesting that responses evoked at the same time interval as the N2 component identified in the current study are generated in the right cortex during the perception of sound motion and sound localization. Right hemisphere activation has been observed in the right parietal lobe (Griffiths et al., 1998; Ducommun et al., 2002; Xiang et al., 2002; Zatorre et al., 2002) as well as the right insula (Griffiths et al., 1994). Baumgart and colleagues (1999) identified activation of the right planum temporale in response to illusionary sound motion resulting from ITD manipulation. Finally, acoustic cues to auditory distance perception such as sound intensity variations specifically activate the right supratemporal plane (Seifritz et al., 1999). Hence, since the N2 component seems to be particularly suited to measuring children’s brain responses to moving sounds. Indeed, scalp asymmetry in the N2 amplitude was only present in response to sound movement. Responses to auditory gaps evoked a bilateral scalp activation pattern in both groups.

N2 amplitude in response to left movement was significantly greater in the good listeners as compared to the poor listeners, which could conceivably reflect (1) immature auditory processing in the poor listeners, (2) better perception of left moving sounds by good listeners than by poor listeners, and (3) better synchrony along the auditory pathway in the good listeners. During childhood, N2 amplitude increases with age and reaches its maximal value around 10–11 years of age. Afterwards it decreases gradually and reaches adultlike values consistently at 17 years of age (Ponton et al., 2000). Furthermore, N2 amplitude increases as the stimulus becomes more readily discernable (Ungan and Özmen, 1996). It is important to note, however, that further research involving younger children is needed to document the maturational time course of auditory movement detection before one could assert that the differences demonstrated here are due to maturational changes.

Initially the effect of longer latencies over the right hemisphere, where N2 amplitude is largest, seems peculiar in that long latencies are typically associated with small amplitudes if both measures represent the same neurophysiological mechanism (Ungan and Özmen, 1996). One possible explanation for this difference is that two neurophysiological mechanisms are represented. Based on the grand averages for the observed latency interaction effect of hemisphere by group (Figure 7), we noticed that the longer latency at FC4 reflected an additional negative shift, earlier referred to as N2′, which was only noted in the good listeners. Given that this effect was combined across directions of sound movement, we could hypothesize that N2′ is the manifestation of the right hemisphere predominance for sound localization remarked upon in the literature (Baumgart et al., 1999; Ducommun et al., 2002; Zatorre et al., 2002; Mathiak et al., 2003). The absence of N2′ in our poor listeners, combined with bilateral N2 voltage distribution, suggests a lack of right hemisphere dominance for sound localization in this subject group. Bilateral representation of function has been thought to reflect a lack of maturation (Bryden, 1982; Estes et al., 2002). This finding is in concordance with previous accounts on brain activation patterns for children with learning problems (Cunningham et al., 2000; King et al., 2002; Wible et al., 2002). A difference in the myelination process and synaptogenesis has been put forward as one reason why children with poor listening skills might show different patterns in their evoked potentials (Liasis et al., 2003). Based on this premise, it is not surprising that we registered differences between subject groups in the N2 and N2′ amplitude and latency as age-related changes in the N2 component appear to be caused by
“biological brain maturation in terms of synaptic count decrease, myelination, developing inhibitory control, rather than by substantial changes in the N2 function” (Čeponienė et al, 2002, p. 881).

As stated earlier, sound localization and movement are based on binaural cues (i.e., ITDs and IIDs) as well as monaural cues (e.g., intensity changes). On the other hand, gap detection does not rely on the processing of binaural or monaural intensity cues. While no group differences were found for the N2 in response to auditory gaps, the N2 in response to sound movement differed between poor and good listeners. Based on our findings, we cannot discern whether the ERP differentiations are in response to the monaural or binaural characteristics of the stimuli. Monaural intensity changes have been found to evoke larger responses in the right hemisphere, more specifically in the right supratemporal plane, one of the N2 generators in children. Strictly speaking, “purely intensive mechanisms” (Ungan and Özmen, 1996, p. 486) could be solely responsible for larger activity in the right hemisphere (Belin et al, 1998; Mathiak et al, 2003). Nonetheless, brain activation patterns still differ between good listeners and poor listeners in response to auditory movement. Whether differences in the N2 component between poor and good listeners are primarily evoked by the monaural or binaural intensity cues within the stimulus should be addressed in subsequent studies specifically designed to evaluate this question.

CONCLUSION

Scalp activation patterns in children with poor listening skills show less right hemisphere predominance for auditory movement perception in the long-latency obligatory N2 component when compared to age-matched children with good listening skills. These disparities could be due to maturational differences between poor and good listeners, better synchrony along the auditory pathway, or increased salience for moving sounds in good listeners.

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REFERENCES


