

# ERP Evidence of a Dichotic Left-Ear Deficit in Some Dyslexic Children

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## Abstract

Children with and without behavioral dichotic left-ear deficits participated in an event-related potential study with quasidichotic presentations of familiar fairy tale segments. Electrical activity was recorded from the scalp while the children listened for semantically and/or syntactically anomalous words from either the right side or the left side while competing segments of the fairy tale were simultaneously presented from the opposite side. Latencies and amplitudes were averaged for each target condition within the group with dichotic left-ear deficits (LED) and the group with normal dichotic listening performance (WNL). Individual global field power waveforms and topographic brain maps were generated for the average response in each of the two listening conditions, target right and target left. Cross-correlations were performed on the grand averaged global field power waveforms to measure the degree of synchrony between target right and target left responses in both groups. Integration functions were performed to compare the accumulated sum of voltages during target (right and left) and control (right and left) conditions. WNL children produced typical ERP responses to the target words in both target right and target left conditions. Responses from LED children were at delayed latencies in the target left condition and were at reduced amplitudes in both target conditions. Topographic brain maps revealed more lateralized scalp distributions and greater activation of frontal regions in LED children in the target left condition. Cross-correlational and integration function results demonstrated interaural asymmetries in responses from the LED children. Overall results suggest that slowed neural conduction times, poor interhemispheric transfer of neural activity, and a failure to suppress competing information arriving at the right ear may be involved in poor left-sided processing in children with behavioral left-ear dichotic deficits.

**Key Words:** Auditory processing disorder, children, dyslexia, event-related potential, global field power, integration, topographic brain map

**Abbreviations:** ANOVA = analysis of variance; EEG = electroencephalic; ERP = event-related potential; GFP = global field power; HEOG = horizontal electro-oculographic; LED = left-ear deficit; SCAN-C = Screening Test for Auditory Processing Disorders—Children; VEOG = vertical electro-oculographic; WNL = within normal limits

## Sumario

Niños con y sin deficiencias dicóticas conductuales del oído izquierdo participaron en un estudio de potenciales relacionados con el evento, con presentaciones cuasi-dicóticas de segmentos familiares de cuentos de hadas. La actividad eléctrica se registró en el cráneo mientras los niños escuchaban buscando palabras anómalas, semántica o sintácticamente, tanto del lado derecho como del lado izquierdo, mientras que se les presentaban simultáneamente segmentos competitivos del cuento de hadas en el lado

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opuesto. Se promediaron las latencias y las amplitudes para cada condición dentro del grupo con deficiencias dicóticas en el oído izquierdo (LED) y del grupo con desempeño auditivo dicótico normal (WNL). Se generaron ondas de poder de campo global individuales y mapas topográficos cerebrales, para la respuesta promedio en cada una de las dos condiciones auditivas: meta en el lado derecho y meta en el izquierdo. Se realizaron correlaciones cruzadas con el gran promedio de las ondas de poder de campo global, para medir el grado de sincronía entre las respuestas con meta en el lado derecho o meta en el izquierdo, en ambos grupos. Se realizaron funciones de integración para comparar la suma acumulada de voltajes durante las condiciones meta (derecha e izquierda) y control (derecha e izquierda). Los niños WNL produjeron respuestas ERP típicas ante las palabras meta, tanto en condiciones de meta derecha o meta izquierda. Las respuestas de los niños LED mostraron latencias retardadas en las condiciones de meta izquierda y mostraron amplitudes reducidas en ambas condiciones meta. Los mapas topográficos revelaron distribuciones craneales más lateralizadas y mayor activación de las regionales frontales en los niños LED, en la condición meta izquierda. Las funciones de integración y de correlación cruzada demostraron asimetrías interaurales en las respuestas de los niños LED. Los resultados globales sugieren que el hallazgo de tiempos de conducción neuronal lentos, una pobre transferencia de actividad neuronal inter-hemisférica y una falla para suprimir información competitiva que arriba al oído derecho, puede estar involucrado en un pobre procesamiento del lado izquierdo, en niños con deficiencias conductuales dicóticas del oído izquierdo.

**Palabras Clave:** Trastornos de procesamiento auditivo, niños, dislexia, potencial relacionado con el evento, poder de campo global, integración, mapa topográfico cerebral

**Abreviaturas:** ANOVA = análisis de variancia; EEG = electroencefalografía; ERP = potencial relacionado con el evento; GFP = poder de campo global; EGO = electro-oculografía horizontal; LED = deficiencia del oído izquierdo; SCAN-C = Prueba de Tamizaje para Trastornos de Procesamiento Auditivo en Niños; VEOG = electro-oculografía vertical; WNL = dentro de límites normales

Children with language and reading difficulties have been shown to perform poorly on tests of dichotic listening. They often show a large interaural asymmetry with normal performance in the right ear and significantly reduced performance in the left ear (Morton and Siegel, 1991; Lamm and Epstein, 1994; Moncrieff and Musiek, 2002). Because a similar pattern of performance has been observed in patients with a split or disordered corpus callosum, it has been suggested that children with a left-ear deficit during dichotic listening may have poor interhemispheric transfer of information from the right hemisphere to the left hemisphere following left ear input of speech material (Jerger et al, 1986; Musiek et al, 1984, 1988). Studies using auditory event-related potentials to explore differences in the interhemispheric transfer of information in children with reading

disorders have reported delayed latencies and reduced amplitudes across a range of responses, beginning at approximately 100 msec following stimulus input. A poor interhemispheric transfer hypothesis has been partially supported by evidence of delayed neural transmission in children with language, learning, and reading difficulties in studies utilizing both nonspeech stimuli (Jirsa and Clontz, 1990; for review, see Lepannen and Lyytinen, 1997) and dichotic speech stimuli (Jerger, Thibodeau, et al, 2002). Deviant and nonfocal topographic brain maps have also been reported for responses from language-impaired children (Tonnquist-Uhlen, 1996).

Many children with language and reading disorders are able to perform at normal levels on dichotic listening tasks for input to the right ear and only show a significant deficit for input to their left ear.

Because the deficit may be specific to the left ear, electrophysiologic techniques that examine and contrast input to both the right and left ear during competitive listening tasks may prove useful in identifying specific weaknesses in these children. Standard behavioral testing with dichotic listening material uses pairs of consonant-vowels, digits, or single-syllable words presented through headphones to a listener seated in a sound-isolated booth. These methods are used to diagnose a left-ear deficit type of auditory processing disorder in children, but they may lack ecologic validity as a method for evaluating a child's ability to process auditory information in real-world situations such as those encountered in a classroom. In school, children must be able to listen to ongoing speech in order to extract the information necessary for learning. As such, they must be able to maintain auditory vigilance while focusing attention on the most relevant stimuli and suppressing auditory information that is of less importance to the learning task.

A recently developed procedure for recording the auditory event-related potential (ERP), patterned loosely after a vigilance task, permits an evaluation of precise temporal characteristics of the neural response following the input of complex speech more similar to the kind that children must follow during routine tasks of listening and learning in school (Jerger, Greenwald, et al, 2000). As previously described (Jerger, Moncrieff, et al, 2000), the procedure is quasidichotic, involving the presentation of segments from the fairy tales "Cinderella" and "Snow White" through loudspeakers situated directly to the right and to the left of the child's head. The child is asked to listen for segments presented through one speaker at a time and to ignore the different segments being simultaneously presented from the other speaker. The task is to signal every time a semantically and/or syntactically anomalous word is presented through the monitored speaker. By recording the responses to anomalous words presented both to the right and left ears, it is possible to analyze the ERP response not only for amplitude and latency characteristics following speech input per se, but also for the interaural differences that may occur during monitoring of one ear while suppressing input to the other ear, a task that directly relates to behavioral dichotic listening tests. As

reported, the anomalous words produced an ERP in normal children and young adults with a robust positivity at a latency of approximately 800 to 900 msec with no significant interaural differences observed in the responses (Jerger, Moncrieff, et al, 2000).

From individual average waveforms, both traditional and global field power (GFP) measures of latency and amplitude can provide information about intra-aural and interaural differences in the neural response. Traditional measures are derived from electrode locations where maximum activation occurs, usually at centroparietal sites centered at electrode CPz. This type of analysis can reflect whether an individual subject or group of subjects demonstrates typical latency and amplitude characteristics at the region of the scalp where the ERP most often occurs. The global field power (GFP) waveform (Skrandies, 1989, 1990) takes into account the activity at all electrodes and resolves the dilemma over determining the appropriate electrode at which to measure response latency in individual children. An advantage to the GFP method is that it can demonstrate instances in which an ERP response occurs at electrode sites that differ from the standard centroparietal locations. Topographic maps derived from the maximum response latency in the GFP waveform can then be used to display its scalp distribution in order to determine if the response is shifted from the expected centroparietal scalp locations. It has been suggested that in studies where neuromaturation factors may result in disordered responses, topographic mapping differences may prove more important than standard latency and amplitude characteristics from the ERP (Stauder, et al, 1989).

The overall goal of this study was to investigate whether the ERP recorded during a quasidichotic listening task would differ in children who had previously demonstrated interaural asymmetries during behavioral dichotic listening tasks. It was hypothesized that results following input to the left ear would differ in children with a dichotic left-ear deficit, both from the results in the same children following input to the right ear and from results obtained in the left ears of children with normal dichotic listening performance. Several methods were used to examine differences in the ERP from children with behavioral left-ear deficits.

## METHOD

### Subjects

A total of 20 children were tested in a preliminary study to determine measures of interaural asymmetry during behavioral dichotic listening testing (Moncrieff and Musiek, 2002). As previously described, half of the children had been previously diagnosed as dyslexic, and the other half were performing normally in school. Children with dyslexia were chosen for the study because they were predicted to be the most likely group of children to demonstrate a left-ear deficit on dichotic listening tests. All children were 11 to 12 years old at the time of the study, and all were strongly right-handed as assessed by a handedness survey (Annett, 1970). All children had normal (Type A) tympanograms and hearing sensitivity at 15 dB or better across the frequencies from 500 to 4000 Hz. None had been diagnosed with attention deficit disorder with or without hyperactivity, psychiatric disorder, or neurological impairment. Only monolingual

native speakers of English were included in the study. In each half, there were seven males and three females.

Behavioral dichotic listening tests were used to measure interaural asymmetry in all of the children. A larger than normal interaural asymmetry was defined as significantly reduced performance in the left ear together with normal performance in the right ear, resulting in a significantly large difference in performance between the two ears. The 20 children were divided into two groups based on results from the Competing Words subtest of the SCAN-C (Keith, 1986) as illustrated in Table 1. Asterisks are placed beside the initials of each child whose performance indicated a left-ear deficit, defined as performance below 76% in the left ear (Moncrieff and Musiek, 2002), together with an interaural difference greater than 10%. As seen in Table 1, seven of the dyslexic children (five males and two females) demonstrated poor performance in the left ear and a large interaural asymmetry on the Competing Words test. This group is referred to as Left-Ear Deficit (LED). The remaining three dyslexic children (two males and one female) and all of the control children

**Table 1. Competing Words Test Results**

Subject	Dyslexic	Right Ear	Left Ear	Ear Advantage	Group
01*	yes	94	66	28	LED
02*	yes	74	56	18	LED
03*	yes	82	60	22	LED
04	yes	86	76	10	WNL
05	yes	80	76	4	WNL
06	yes	86	80	6	WNL
07*	yes	94	70	24	LED
08*	yes	96	74	22	LED
09*	yes	84	70	14	LED
10*	yes	86	74	12	LED
11	no	90	82	8	WNL
12	no	76	70	6	WNL
13	no	92	78	14	WNL
14	no	86	80	6	WNL
15	no	96	86	10	WNL
16	no	92	88	4	WNL
17	no	86	84	2	WNL
18	no	92	88	4	WNL
19	no	80	76	4	WNL
20	no	90	88	2	WNL

demonstrated normal results on the Competing Words subtest for both left ear performance and/or interaural asymmetry and are referred to as "Within Normal Limits" (WNL). One control child (12) demonstrated reduced performance in the left ear, but performance in the right ear was also below normal. Another control child (13) demonstrated an interaural asymmetry greater than 10%, but left-ear performance was above 76%. Since neither of those children demonstrated both performance deficits, they could not be characterized as left-ear deficit and were therefore included in the WNL group.

### **Test Stimuli**

A complete description of the test paradigm has been previously described (Jerger, Greenwald, et al, 2000). A total of 200 segments of the fairy tales "Cinderella" and "Snow White" were recorded by a male voice. Segments were approximately equivalent in length. In half of the segments, chosen randomly, one word was replaced with a target anomalous word. The test stimuli were stored in digital form and delivered to the subject via digital-to-analog conversion. Segments of the fairy tales were presented in normal sequence, with the sequence in one channel delayed by about 80 seconds relative to the presentations in the other channel.

### **Electrophysiologic Methods**

For presentation through the two loudspeakers, the sequence of 200 segments was divided into eight blocks of 25 segments each. Each child was directed to attend to four blocks of segments presented through the speaker directly opposite one ear while ignoring those presented through the speaker directly opposite the other ear. Thus, half of all presentations were to be attended right and half were to be attended left. Because half of all presentations contained anomalous words, there were 50 segments containing anomalous words (target) and 50 segments not containing anomalous words (control) presented toward each ear throughout the experiment. Because there is an advantage to the first hemispace toward which attention is directed (Boliek et al, 1988), the first side to be attended was randomly assigned across all subjects.

The child was seated comfortably in a medical examining chair. All sequences were delivered from two loudspeakers at ear height and one meter to the left and right of the child's ears. A 38 cm computer screen, placed at eye level 1.7 meters in front of the child, presented graphic directions pertaining to the procedure. At the beginning of each block of 25 segments, the child was directed either to listen right (with a red screen and an arrow pointing toward the right) or to listen left (with a blue screen and an arrow pointing toward the left). In order to reduce eye movement throughout the procedure, the child was further directed to focus attention on a small, plastic character doll located directly below the computer screen. Cotton balls were taped across the child's eyelids to limit the magnitude of excursions during eyeblinks throughout the experiment.

### **Electrophysiologic Recording Apparatus**

Brain electrical activity was recorded from 32 silver-silver chloride electrodes. Thirty electrodes were mounted in an elastic cap (Neuroscan QuickCap), and two were mounted above and below the left eye in order to monitor vertical electro-oculographic (VEOG) activity. Electrical activity was referred to linked mastoid electrodes with  $F_{Pz}$  as ground. Individual sweeps of electroencephalic (EEG) activity, time-locked to the onset of target and nontarget words, were stored in a continuous file for offline analysis. Ongoing EEG activity was amplified and bandpass, analog filtered from 0.15 to 125 Hz. Analog filter skirts were sloped at -12 dB per octave. The amplified and filtered EEG activity was then digitized through an acquisition interface system (Neuroscan Synamp) and routed to a computer for individual sweep storage, display, averaging and post hoc digital filtering (SCAN 4.0). Signal averaging was carried out after offline artifact rejection and baseline correction. Individual epochs were examined and rejected whenever electrical activity in the eye channel (VEOG) exceeded  $\pm 30$  microvolts. If more than 30 of the 50 epochs of a given target or nontarget condition were rejected for any reason, then the entire data set for that subject was rejected. Thus, each average ERP was based on a minimum of 20 epochs. Successfully averaged evoked potentials were

then linearly detrended, digitally low-pass filtered at 20 Hz, and baseline corrected. Digital filter slope was -48 dB per octave.

### Electrophysiologic Procedure

Prior to testing, the speech levels from the two loudspeakers were adjusted to achieve median plane localization for each child as previously described (Jerger, Moncrieff, et al, 2000). All stimuli were presented at the levels determined through this localization procedure so that neither ear enjoyed an intensity advantage as the result of an interaural asymmetry in sensitivity. After affixing the electrode cap to the head, the child was instructed to look at the computer screen and to listen only to the fairy tale presentations arriving from whichever side the screen directed them to monitor. They were told to remain still and to blink normally, limiting eyeblinks as much as possible. Each child was told to press the button on the same side of the response pad as the speaker being monitored whenever a word was heard from that speaker that did not fit in the fairy tale story. In this way, while monitoring the right speaker, only the right-sided button on the response pad should have been pressed, and while monitoring the left speaker, only the left-sided button on the response pad should have been pressed. Responses were monitored throughout the experiment to assure that the child remained on task, but the responses were not recorded for accuracy.

### Data Analysis

In order to eliminate significant sinusoidal modulation seen in waveforms filtered at 20 Hz and to facilitate measurement of peak responses, individual subject waveforms were reanalyzed at digital low-pass filter settings of 6 Hz (filter slope of -12 dB per octave). Epochs were separately averaged for target right (anomalous words presented through the right sound field speaker) and target left (anomalous words presented through the left sound field speaker). Individual average waveforms in each of the two conditions were analyzed for peak amplitudes and latencies at the centroparietal (CPz) electrode site. Absolute latencies and amplitudes of the negative early response characterized as N400 and the positive later response characterized as

P800, together with peak-to-peak amplitudes from the two responses, were measured for each individual subject. Individual global field power (GFP) waveforms were also computed in order to derive a single measure of peak latency and amplitude for each child from multiple electrodes across the scalp. GFP is defined by calculating, at each time sample of the epoch, the square root of the mean of the squared derivations of each voltage from the common average reference voltage. The resultant value is a GFP waveform plotted as a function of time across the entire epoch.

Individual latency and amplitude information were measured both at electrode site CPz and at the peak of the GFP waveform. Mean latency and amplitude information within each group, defined on the basis of behavioral test performance (WNL and LED), were compared for the target right and target left conditions. A mixed-design analysis of variance (ANOVA) was used with one between-subjects factor (group) and one within-subjects factor (target condition). Post hoc comparisons were conducted by independent samples t-tests constrained by Levene's test for equality of variances. Statistical significance was evaluated at an alpha level of 0.05.

Topographic brain maps of the GFP waveforms were constructed by interpolation of voltages between adjacent electrodes, using a 4-point linear-interpolation algorithm. Bivalent colors representing the range of observed voltages were then assigned to the resulting voltage matrix.

A cross-correlation function was performed on the grand averaged response for each group. The cross-correlation function computes a standard Pearson product-moment coefficient of correlation ( $r$ ) from the voltage levels obtained at each of 1000 1 msec time intervals across the waveform. When one waveform (target right) is compared to a different waveform (target left) from the same individual subject or group of subjects, the cross-correlation function measures the coefficient of correlation as one waveform is displaced in time relative to the other waveform by a specified time interval (1 msec). The final plot of the coefficient,  $r$ , as a function of time displacement,  $\tau$ , will reflect the extent to which brain activation in response to one target condition correlated with brain

activation in response to the other target condition. If the two waveforms are identical, they will achieve perfect correlation ( $r = 1.0$ ) at a tau value of 0. When the two waveforms are different, the displacement in the peak of the cross-correlation function quantifies the extent to which one waveform would need to be delayed in time relative to the other waveform for the two waveforms to achieve maximum synchrony. In this way, a cross-correlation of the target right and target left waveforms can provide a measure of the asynchrony between the response obtained when listening with the right ear and when listening with the left ear.

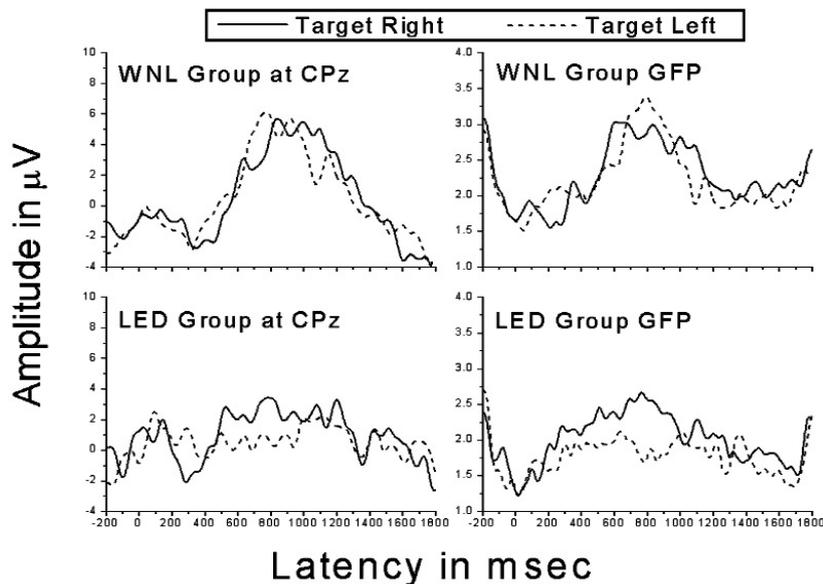
A final approach examined results when the individual averaged response at CPz to each target condition (target right and target left) was integrated across the time interval and compared to the individual averaged response at CPz to the corresponding control conditions (control right and control left). The control condition is defined as the average response when the child listened to the fairy tale segments from one side (right or left) that did not contain anomalous words. Integration functions are useful in oddball paradigms such as mismatch negativity, P300 and this type of anomalous task because they clearly differentiate the waveform obtained during the control condition from the waveform

obtained when the listener has perceived a target anomalous word. The integration function computes an accumulation sum of the voltages across each sweep by multiplying each data point by an interpoint distance. The resultant integrated sum of the waveform should be small in the control condition and demonstrate a significant increase in accumulated voltages when listeners have attended to oddball targets. A standard integration function reflects accumulated voltages in both the negative and positive directions. Alternatively, an integration function performed on a rectified average waveform will convert all voltages into positive values prior to summing them. In this way, the rectified integration function reflects the overall increase in brain activation without regard for direction of the response.

## ELECTROPHYSIOLOGIC RESULTS

### *Average Responses at CPz*

Grand average waveforms for the response at electrode site CPz for each of the two groups are displayed in the left-hand column of Figure 1. In the WNL group, waveforms are similar for the two listening conditions with a negative peak at a latency



**Figure 1.** Grand averaged waveforms of the ERP in the target right and target left conditions in both groups at electrode site CPz (left-side waveforms) and grand averaged global field power waveforms in the target right and target left conditions in both groups (right-side waveforms).

**Table 2. Means and (Standard Errors) of Latencies and Peak-to-Peak Amplitudes of P800 Response at CPz in Two Groups and Two Target Conditions**

Group	Target Right		Target Left	
	Latency	P-P Amplitude	Latency	P-P Amplitude
WNL (n = 13)	886.0 (37.1)	14.2 (1.4)	823.4 (24.5)	13.4 (1.1)
LED (n = 7)	1000.0 (68.8)	9.1 (1.4)	1217.1 (59.8)	8.7 (0.8)

**Means and (Standard Errors) of Latencies and Amplitudes of Peak in Individual GFP Waveforms in Two Groups and Two Target Conditions**

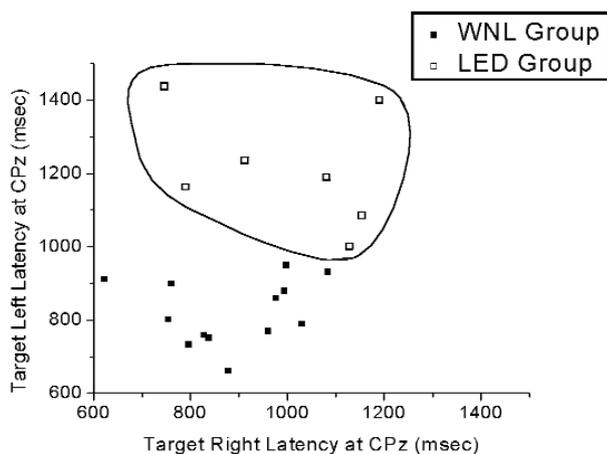
Group	Target Right		Target Left	
	Latency	Amplitude	Latency	Amplitude
WNL (n = 13)	856.8 (73.7)	4.35 (0.36)	797.7 (26.9)	3.94 (0.35)
LED (n = 7)	830.9 (115.9)	3.57 (0.52)	823.4 (134.81)	2.81 (0.19)

of approximately 300 to 350 msec and a positive peak at a latency of approximately 800 to 900 msec. Latencies are slightly earlier and amplitudes are slightly larger in the target left condition, but the differences between the two conditions are slight. In the LED group, the waveforms are dissimilar. In the target right condition, there is a negative peak at a latency of approximately 300 msec and a positive peak at a latency close to 800 msec, but the amplitudes of these responses are smaller than in the WNL group. In the

target left condition, there is no apparent negative peak, and there are several positive peaks with no clear maximum across the grand averaged response. Overall, amplitudes for the target left condition in the LED group are indistinguishable from baseline across the latency region typical for this ERP.

Group averages and standard errors for latency and amplitude measures across the two listening conditions are summarized in the top half of Table 2. With respect to latencies of the P800 response, a mixed-design ANOVA showed a significant main effect for group ( $p = .001$ ) and for the interaction between target and group ( $p = .009$ ), but no significance for the main effect of target condition, right versus left ( $p = .120$ ). Within each of the two groups, post hoc independent samples t-tests on the P800 latencies showed a significant effect for ear in the LED group ( $p = .035$ , equal variances not assumed), but no significance for the effect of ear in the WNL group. Post hoc independent samples t-tests on the P800 latencies in each target condition showed a significant effect for group in the target left condition ( $p = .000$ , equal variances not assumed), but no significance for the effect of group in the target right condition.

A plot of individual P800 latencies in target right and target left conditions, separated by group membership, is displayed in Figure 2. As shown in Figure 2, the P800 latencies in the LED children were distributed differently from those in the WNL children, with longer latencies in the target



**Figure 2.** Plot of the target right and target left latencies for individuals in each of the two groups (WNL and LED) for the P800 response at electrode site CPz.

left condition relative to the target right condition. An enclosure around the latencies for children in the LED group demonstrates that the results for the children in the two groups can be separated along the measure of latency of the P800 response to the target left condition.

For peak-to-peak amplitude, measured from maximum negativity of the N400 response to maximum positivity of the P800 response, a similar mixed-design ANOVA showed no significance for the effect of target condition ( $p = .628$ ) or for the interaction between target condition and group ( $p = .855$ ), but did show a significant main effect of group ( $p = .005$ ). As shown in Table 2, the peak-to-peak amplitude observed in LED children was significantly smaller than in WNL children.

### GFP Waveforms

Grand averages of the individual global field power waveforms for both target right and target left conditions for the two groups of children are illustrated in the right-hand column of Figure 1. The morphology of the GFP waveforms for the two groups is similar to the morphology of the grand average waveforms from electrode site CPz. Again, the GFP waveforms for the WNL group demonstrate a similar response in the two target conditions, with peak response latencies ranging between 600 and 800 msec. In the LED group, the GFP peak in the target left condition is also less distinct than the peak for the target right condition or the peaks in both target conditions observed in the other group of children.

### Topographic Brain Maps

A topographic brain map derived from the peak response in the GFP waveform indicates the region across the scalp where the greatest change in activity was recorded. As previously described for this task, the maximum positivity in each target condition occurred over the centroparietal region at approximately 700 to 900 msec following presentation of the anomalous word (Jerger, Moncrieff, et al, 2000). An individual child's average GFP for a target condition should subsequently reflect the contributions of all electrodes across the scalp at that point in time. If the child's response is normal, maximum positivity will reflect increases in

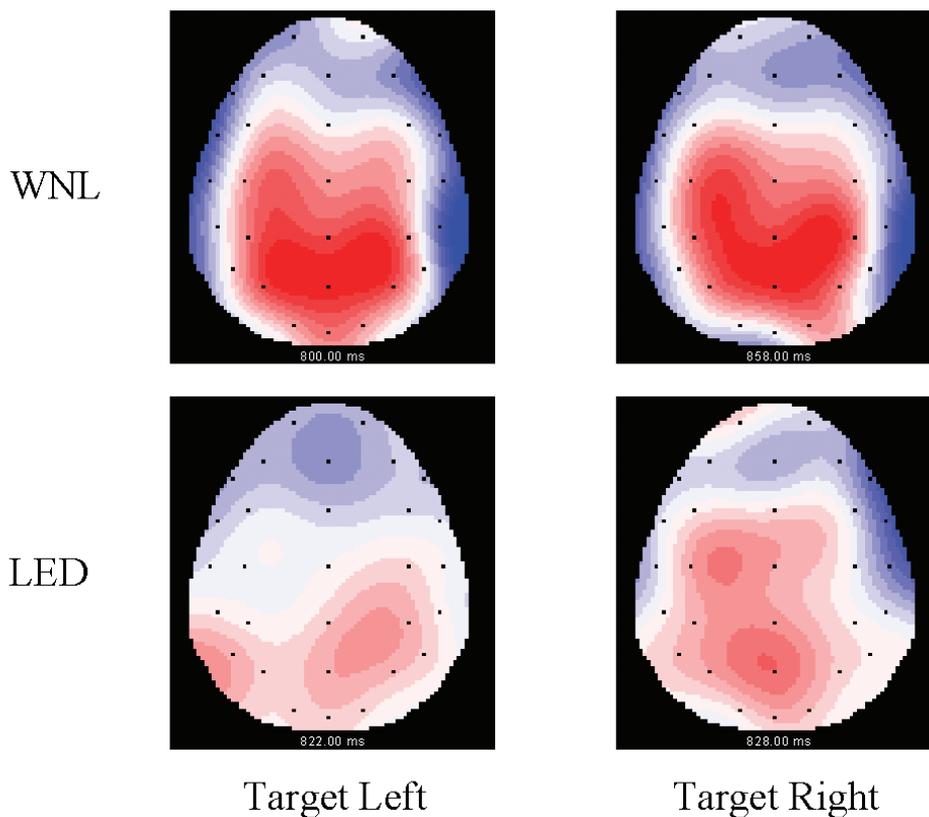
electrical activity centered near the CPz electrode and distributed bilaterally across adjacent electrodes. There are several ways in which the topographic map may reflect abnormal responses in the GFP waveform. Slower neural conduction along typical neural pathways would result in a delayed latency for the peak in the GFP waveform, but the topographic map could still represent maximum positive activation at the normal centroparietal recording site. Secondly, a shift of activity to different regions of the brain that are recruited to help participate in the task could result in a peak in the GFP waveform that occurs across a different region of the scalp at either the same or a different latency. A third possibility is that neural activity is nonfocal and distributed generally across the scalp. In any of these cases, there may also be several peaks in the GFP waveform that represent multiple latencies at which activation achieved similar levels. Multiple peaks in the GFP waveform that occur at comparable amplitudes might reflect increased activation across different scalp locations at different points in time following presentation of the stimulus. Topographic brain mapping methods can resolve the dilemma created by multiple peaks by identifying the peak that represents positive activation at scalp locations that most closely fit the anticipated response pattern.

Topographic brain maps were created at the peak of the GFP waveform in target right and target left conditions for each of the children in this study. Table 3 lists the pattern of activation displayed in each topographic brain map, together with the magnitude of the GFP peak for target right and target left conditions. As shown in Table 3, bilateral responses distributed over the centroparietal region are indicated by the letter "B" and were displayed for most of the WNL children. In a few cases, responses in the WNL group were unilateral (R or L) with scalp distribution maximal over the side opposite the ear toward which the targets were being presented. This pattern occurred only once in the WNL group in the target right condition (18) and with three children in the target left condition (04, 06, and 11). Two of these WNL children were among those initially diagnosed as dyslexic, but they had not demonstrated the left-ear deficit on the behavioral dichotic listening tasks and were therefore placed in the WNL group.

**Table 3. Scalp Distribution and Magnitude ( $\mu\text{V}$ ) at Peak of the GFP Waveforms in Two Groups and Two Target Conditions**

Subject	Diagnosis	Group	Target Left	Target Right	Target Right	
01	Dyslexic	LED	R	2.79	B/F	3.53
02	Dyslexic	LED	R/O	2.82	L/O	3.79
03	Dyslexic	LED	L/F	2.27	R/F	2.33
04	Dyslexic	WNL	B	4.58	L	3.68
05	Dyslexic	WNL	B	2.24	B/F	4.74
06	Dyslexic	WNL	B/O	4.00	L/F	3.98
07	Dyslexic	LED	B	2.08	B/F	1.79
08	Dyslexic	LED	L/F	3.31	L/F	4.87
09	Dyslexic	LED	R/F	2.97	R/F	2.99
10	Dyslexic	LED	B/F	3.44	B/F	5.70
11	Control	WNL	B/O	3.54	L	3.78
12	Control	WNL	B/F	2.49	B/F	4.07
13	Control	WNL	B	3.04	B	2.69
14	Control	WNL	B	6.93	B	4.83
15	Control	WNL	B	5.21	B	7.90
16	Control	WNL	B	4.22	B	3.34
17	Control	WNL	B/F	3.20	B	4.88
18	Control	WNL	R	4.55	B	2.85
19	Control	WNL	B	4.30	B/F	4.72
20	Control	WNL	B	2.90	B	4.18

B = bilateral, R = right, L = left, O = occipital, F = frontal



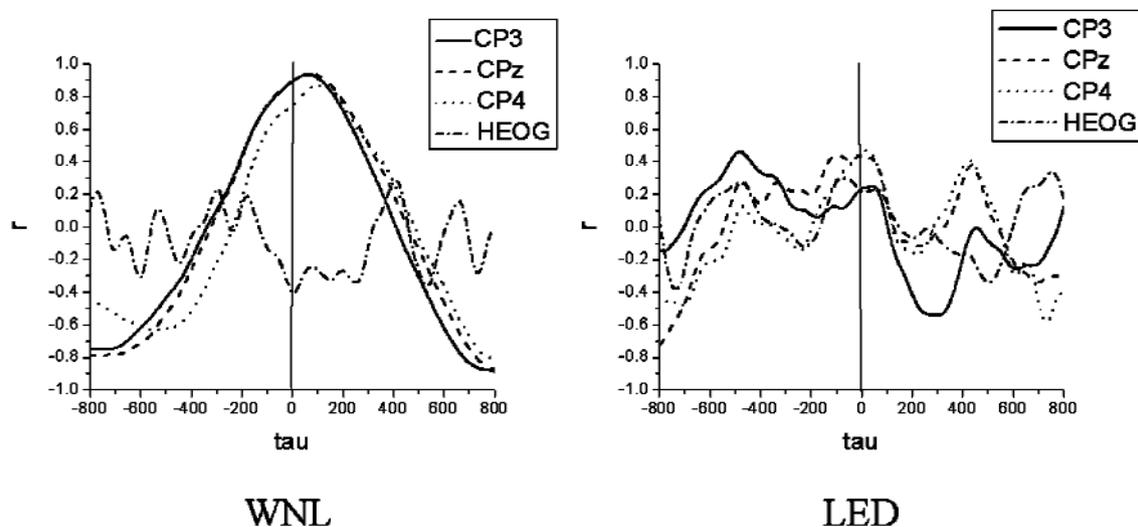
**Figure 3.** Topographic brain maps at the peak of the grand averaged GFP response in two groups and two listening conditions, target right and target left.

Unilateral patterns of activation were observed in a majority of the LED children (5 of 7 in each target condition), usually with distribution in the region of the scalp contralateral to the ear being stimulated. In one case (03), the pattern of activation was ipsilateral to the side toward which the target words were being presented. In another (08), both conditions produced maximum activation only on the left hemisphere side of the scalp. Another notable difference in the maps of the LED children was a shift toward maximum activation in the frontal region of the scalp, with much less positive activation in the centroparietal area.

Mean latency and amplitude information from the individual GFP waveforms are displayed in the bottom half of Table 2. A mixed-design ANOVA on average latencies of the GFP showed no significance for the main effects of target ( $p = .686$ ) or group ( $p = .999$ ) and no significant interaction between target and group ( $p = .753$ ). A similar ANOVA on average amplitudes of the GFP also showed no significance for the main effects of target ( $p = .100$ ) or group ( $p = .065$ ) or for the interaction between target and group ( $p = .520$ ). These results show a trend toward significance for target and group with respect to amplitude. As shown in Table 2, the standard errors for the average latencies were much higher for the GFP analysis than for the analysis at CPz, especially in the LED group. The increased variability in the peak response may make it difficult to quantify group differences on the

basis of the GFP peak values.

Topographic brain maps created at the average latency in the grand averaged GFP response within each of the two groups are displayed in Figure 3. All are scaled to a range of voltages from  $-5 \mu\text{V}$  to  $5 \mu\text{V}$ . As shown in Figure 3, responses were bilateral in both target conditions in the WNL children. The responses for the WNL children were also at greater amplitudes than in the LED children. The distribution of the response for the LED children is more lateralized in both target conditions across the contralateral side of the scalp. The shift toward the left side of the scalp in the target right condition is likely due to the unilateral left-sided responses observed in the individual maps for 4 of the 7 LED children. In the target left condition, activation is more focal over the right hemisphere side of the scalp and fails to demonstrate a frontal spread of activation over the left hemisphere portion of the scalp. Individual responses in the target left condition were highly variable for the LED children. Three of them demonstrated right-sided unilateral responses; two of them demonstrated left-sided unilateral responses; and two of them demonstrated bilateral responses. With this much individual variability in the GFP peak response across the LED group, the grand averaged GFP map displays an overall weakness in the response, but it fails to demonstrate a typical pattern for these children while performing this quasidichotic listening task.



**Figure 4.** Cross-correlation functions at four electrode sites (CP3, CPz, CP4, and HEOG) measuring the synchrony between the target right and target left conditions within each of the two groups.

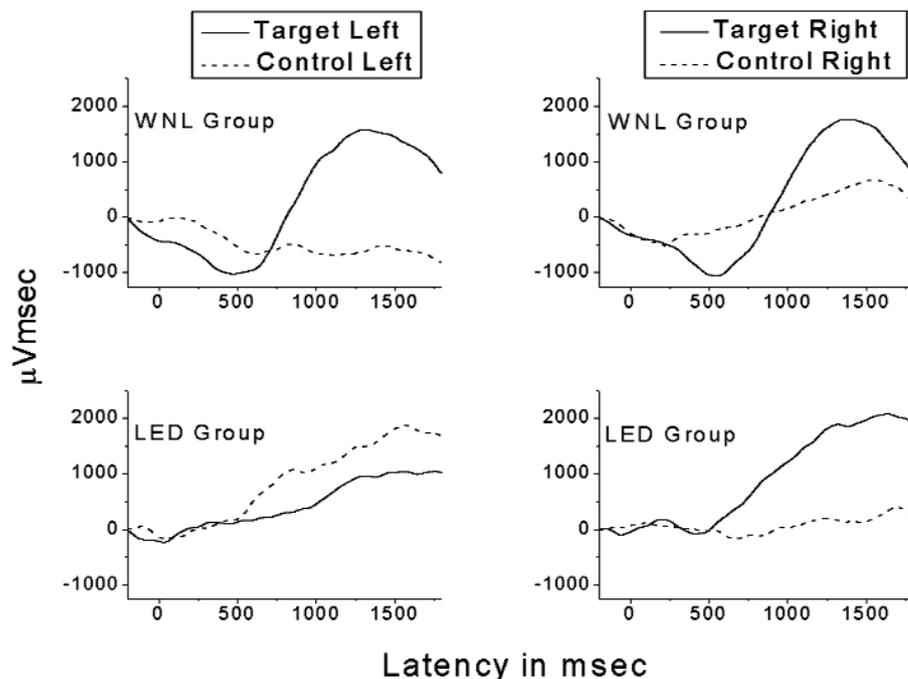
## Cross-Correlation Functions

The cross-correlation functions derived from the grand averaged target right and target left waveforms for the two groups of children are displayed in Figure 4. Functions are derived for three electrodes, the one centered at CPz and the two adjacent electrodes, one toward the left side of the scalp (CP3) and the other toward the right side of the scalp (CP4). As shown in Figure 4, the target right and target left waveforms in the WNL group were highly correlated at all three electrodes (CP3  $r = .919$ , CPz  $r = .904$ , CP4  $r = .850$ ). The tau value is positive at all three electrodes (CP3 tau = 18 msec, CPz tau = 48 msec, CP4 tau = 82 msec). A positive tau value means that in order for the target left waveform to be synchronous with the target right waveform, the target left waveform should be shifted positively (to a later latency) by those values at those electrodes. As a measure of asymmetry between the two target conditions, the high degree of correlation and the low values for tau suggest that the WNL group demonstrated synchronous responses with the overall responses for the left ear occurring slightly ahead of the overall responses for the right ear. Because the HEOG electrode was not activated throughout the experiment,

background brain activity occurring during the acquisition of the ERP is displayed in that electrode's cross-correlation waveform. The highly correlated responses for the WNL group are strikingly dissimilar to the uncorrelated background noise evident in the cross-correlation function for HEOG.

The target right and target left waveforms in the LED group failed to demonstrate a high degree of correlation at any of the three electrodes (CP3  $r = .459$ , CPz  $r = .440$ , CP4  $r = .470$ ). In general, the cross-correlation function within this group is much less distinct from the background brain activity displayed at HEOG. Tau values were also highly variable in the cross-correlation functions for this group. At electrode site CP3, the peak correlation occurred at a tau of -480 msec, and at CPz, the tau value was -120 msec. This would suggest that for the waveforms to be synchronous, the target right waveform would have to be shifted later in time by those amounts.

With respect to individual correlation values at each of the electrode sites, a mixed-design ANOVA showed a significant main effect of group ( $p = .040$ ). When each electrode site was analyzed separately, the group effect was significant only for electrode site CP3 ( $p = .019$ ), although correlation at electrode site CPz approached significance ( $p = .083$ ). An interpretation of these results is that over the



**Figure 5.** Integration functions contrasting the accumulated sum of positive and negative voltages across the recording epoch of the ERP following input of target and control words in both right and left listening conditions and within each of the two groups.

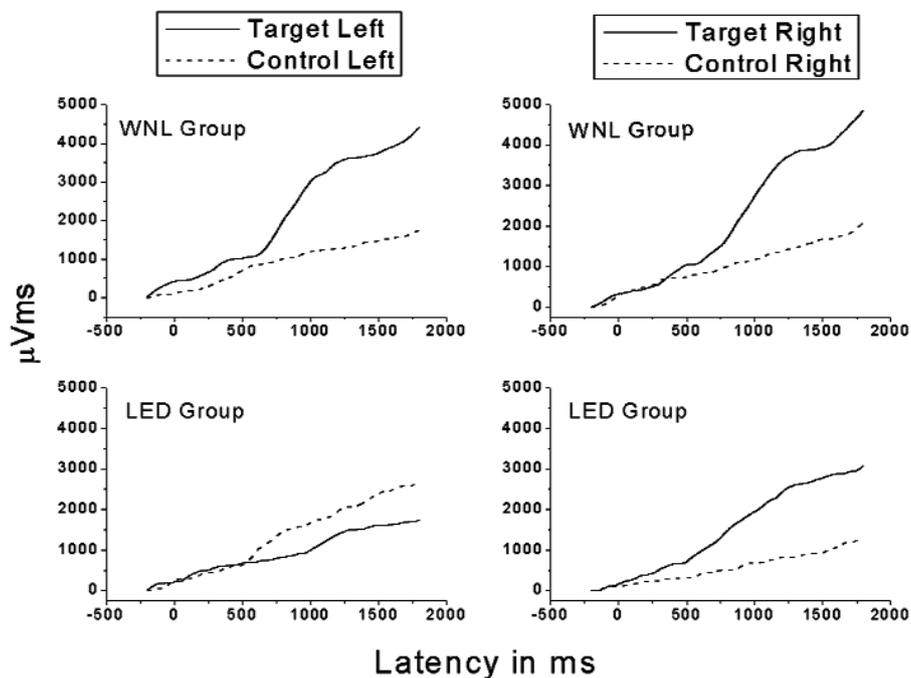
left hemisphere side of the scalp in the LED children, the response to the target right condition occurred at a much shorter latency than the response to the target left condition.

At electrode site CP4, the tau value shifts to 12 msec, suggesting that on the right hemisphere side of the scalp, the relationship between the two target conditions is more synchronous with the target left response occurring at a slightly earlier latency than the target right response. There are secondary peaks for electrodes CPz and CP4, however, at much greater tau values of 436, and 428 msec, respectively. This may be due to greater variability in the individual results for children in the LED group, with some of the children demonstrating a more strongly lateralized response over the contralateral portion of the scalp in both target conditions and others demonstrating a somewhat bilateral response. This cross-correlational evidence of multiple peaks in the LED group suggests that children with a left-ear deficit on behavioral dichotic listening tests may not demonstrate consistent neural activation patterns in the ERP acquired during this quasidichotic listening task. It is possible that in some of the LED children, a failure of the neural activity to synchronize at midline following input to either of the two ears

may have resulted in a more contralaterally lateralized response. In others, the response may have synchronized and spread bilaterally, but at very delayed latencies and reduced amplitudes. A separate analysis of each individual LED child's waveform and topographic maps is needed to overcome the variability involved in the grand averaged group response.

### Integration Functions

Grand averaged responses within each group were subjected to an integration function to derive the accumulated sum of voltages at each electrode across the time interval following presentation of target anomalous words. The same function was performed on the grand averaged responses obtained following the presentation of normal words during control segments of the fairy tale. The purpose of the integration function is to demonstrate that when listeners attend to target presentations, there is a substantial increase in the accumulated sum of voltages across the acquisition period when compared to the response when listeners are attending to normal or control presentations that do not contain oddball or anomalous stimuli. An



**Figure 6.** Integration functions contrasting the accumulated sum of rectified voltages across the recording epoch of the ERP following input of target and control words in both right and left listening conditions and within each of the two groups.

integration function performed on an average waveform will reflect the accumulated sum of voltages in both negative and positive directions across the time interval of the recording epoch. The integration functions comparing the grand averaged response for the target and control conditions within each side of presentation (right and left) are displayed in Figure 5. Each function is derived for the change in voltage at electrode site CPz.

As shown in Figure 5, the WNL group demonstrated a substantial increase in accumulated voltage in the negative direction for the first 500 to 600 msec following presentation of the target words, followed by a substantial increase in accumulated voltage in the positive direction for the next 900 msec. This change occurred regardless of the side toward which the anomalous words were presented. When the same children were listening to fairy tale segments that did not contain anomalous words (the control conditions), their responses reflected a reduced summation of voltage for the right ear and an overall decrease in voltage for the left ear.

Grand averaged responses for the children in the LED group are similar to those for the WNL children for the comparison between target right and control right conditions. The functions reflect much less change in voltage in the negative direction, but demonstrate a substantial increase in the accumulated sum of voltage in the positive direction over the same time interval as seen in the WNL children's responses. The integration functions for the target left versus control left condition in the LED group demonstrate two dramatic differences. First, the integration function for the control condition appears similar to the function for the target right condition. This would suggest that when the LED children were listening to normal fairy tale segments (the control condition) from the left side speaker, their brain activation was summing at the centroparietal electrode in the same manner as during their response to target words arriving from the right side speaker. Throughout each interval that the children were directed to attend for target words arriving from the left side speaker, acquisitions were being made both for target words and for control words. At the same time, the children were instructed to ignore all competing segments being presented from the right side speaker. During approximately

half of the control presentations on the left side, a target word was simultaneously presented from the right side. The similarity in the shape of the integration functions for the control left and target right conditions in the LED group would suggest that some of these children may have failed to suppress the input from the target words on the right side while they were directed to attend to presentations from the left side.

A second difference in the integration function for the target left condition is that the accumulated sum of voltages is lower than the sum of voltages seen in the control left condition. The integration functions for the LED group display the typical pattern for the contrast between target right and control right with a progressively greater accumulated sum of voltages in the target condition. The reversed pattern seen in the target left versus control left condition demonstrates that the neural response in the LED children to the target words arriving from the left side speaker was much weaker than the same response to target words arriving from the right side speaker. It was also weaker than the response that may have occurred as the result of intrusions of target words arriving from the right side speaker when the children were supposed to be attending to control segments from the left side speaker.

A final illustration of this difference can be seen in Figure 6. In Figure 6, the same integration functions are provided for the grand averaged response at electrode site CPz in the two groups of children. In this case, the integration functions were performed after rectifying the waveforms so that all voltages assumed a positive value. In this way, the functions demonstrate the total change from zero that occurred in the voltage in response to the different types of words being processed by the listeners. As seen in Figure 6, both the overall depression in the voltage response in the target left condition and the enhanced voltage response in the control left condition are evident in the function for the LED children.

## DISCUSSION

The purpose of this study was to investigate whether children with left-ear deficits on behavioral dichotic listening performance would produce an ERP response

in a quasidichotic task that differed from the same response in children without left-ear deficits and whether that response would reflect an interaural asymmetry. Several differences in the ERP response were observed in the LED children.

1. The latency of the P800 response at electrode site CPz was significantly delayed in children with a left-ear dichotic listening deficit when they were asked to listen for anomalous words presented from the left sound field speaker. Average latencies to anomalous words presented from the right sound-field speaker were also delayed relative to the latencies from the WNL children, but the differences failed to reach significance. This result is consistent with previous findings of delayed latencies in cortical responses in children with auditory processing disorders (Jirsa and Clontz, 1990), language disorders (Tonquist-Uhlen, 1996), and reading disorders (Mazzotta and Gallai, 1992). Results from this study differ from previous studies in demonstrating that delays in latency were more pronounced for input to the left ear and were significantly different from delays in latency for input to the right ear in children with dichotic left-ear deficits. This evidence of an interaural asymmetry in the ERP is consistent with the behavioral evidence of more normal processing in the right ear and significantly reduced performance in the left ear.

2. Children with dichotic left-ear deficits produced a response to target anomalous words that was significantly smaller than the response observed in children without left-ear deficits. This result is consistent with reduced amplitudes reported in previous auditory ERP studies (Holcomb et al, 1986; Pinkerton et al, 1989; Erez and Pratt, 1992; Mazzotta and Gallai, 1992). In general, LED children produced smaller amplitudes in the target left condition than in the target right condition, but the LED children also demonstrated lower amplitudes in the target right conditions. As a result, an interaural asymmetry in the LED group with respect to amplitudes of the response could not be confirmed.

3. The topography of the grand averaged GFP responses did not reveal clear group differences in the ERP response. The variability observed in the LED children's

individual topographic maps suggests that there may be several factors involved in a failure to produce a normal P800 response when listening in the target left condition. The bilateral and centroparietal scalp distribution observed in the topographic maps for two LED children suggests that an interhemispheric transfer of information through fibers of the corpus callosum may have been involved in their responses. Strongly lateralized features of the topographic brain maps for three of the other five LED children's responses, however, are more consistent with the poor interhemispheric transfer hypothesis. In those cases, the response in the target left condition was lateralized over the right hemisphere side of the scalp with little evidence of crossover to the other side at the peak of maximum activation. In the remaining two cases, the pattern of activation was strongly lateralized over the left hemisphere side of the scalp in the target left condition. Many of the responses also involved a significant amount of activity in the frontal regions of the scalp. Increased electrical activity at frontal scalp locations in the LED children is consistent with evidence that in some dyslexics, frontal regions of the brain, possibly those necessary for allocation of attentional resources, may be recruited to assist with difficult processing tasks (Georgiewa et al, 2002; Shaywitz et al, 2002).

4. Cross-correlational results in the LED children provide additional support for significantly longer latencies in the target left condition for responses over the left hemisphere portion of the scalp. The presence of additional peaks in electrodes located over the right hemisphere portion of the scalp lend support to the possibility that in some of the LED children, results may have been more strongly lateralized in the target left condition than is evidenced by the topographic brain map results. The possibility that activation was strongly lateralized in both target conditions (over the left side in the target right condition and over the right side in the target left condition) would suggest that poor interhemispheric transfer of neural activity was involved in some of the LED children's weaker responses.

5. The integration functions for the LED children provide additional support for an

interaural asymmetry in this quasidichotic listening task. Both the standard and rectified integration functions clearly demonstrate that even though the response in the target right condition was somewhat reduced, the accumulated voltages in the target condition surpassed the voltages seen during the control condition on that side. When the LED children were listening on the left side, the relationship between the target and control conditions was reversed with the sum of voltages in the target condition failing to surpass those seen in the control condition. The similarity in the shapes of the target right and control left functions suggests that when the children were supposed to be attending with their left ear, the response that occurred during control conditions may have been stimulated by target words arriving at the right ear. This suggests an increased dominance of the right ear in these children that may have resulted in a failure to appropriately suppress input from the nonattended side.

In summary, several of the methods used in the analysis of the ERP produced differences between the WNL and LED children. Longer latencies and reduced peak-to-peak amplitudes of the P800 response in LED children were apparent in the traditional analysis of the grand averaged waveforms at the centroparietal electrode site. Analysis by cross-correlation of the grand averaged waveforms also revealed evidence of delayed latencies in the LED children's responses. Despite the failure of the GFP analyses to reveal significant group differences, the topographic brain maps derived from the GFP waveforms demonstrated smaller amplitudes in the LED children across both listening conditions. Generally reduced neural activation in the LED children in response to the target conditions was also evident in the integration functions derived from the grand averaged ERP waveforms.

Interaural asymmetry in the LED children was demonstrated by significant differences between the two ears for average latencies of the P800 response as measured at CPz. Topographic brain maps from LED children also differed between target conditions. Maps created from the grand averaged GFP response in the target right condition showed a more lateralized response with altered distribution toward more frontal

regions. Those contrasted with the diffuse, low-level, and bilateral response observed in the target left condition. Overall, topographic brain maps demonstrated that in the target left condition, responses from the LED children could not be described on the basis of the grand averaged response. Instead, individual maps needed to be evaluated to determine the pattern of response seen in each of the LED children's GFP waveform. The cross-correlation of the target right and target left conditions revealed that LED children did not demonstrate synchronous brain activity during this listening task. Together with the variability in the topographic brain maps, the presence of multiple peaks in the cross-correlation results suggests that some LED children may have demonstrated lateralized activation patterns whereas others may have demonstrated more bilateral responses.

Even with factors related to age, intelligence, handedness, and attention deficit disorder all controlled in this small group of children with behavioral left-ear deficits, there was considerable variability in the electrophysiologic responses observed during this listening task. Because the LED children in this study were all dyslexic, it is possible that some of the group differences may have stemmed from additional factors that were not controlled. Dyslexia is a language-based disorder that may not have interfered with right-ear processing during standard behavioral dichotic tests but may have resulted in bilateral deficits in some of the children when listening to more complex speech information during the quasidichotic listening task utilized in this study. In some of the LED children, the electrophysiologic responses indicated that performance in their right ears was closer to normal as it had been during the behavioral dichotic listening tests. In others, the ERP response was different for both ears, suggesting that disordered language processes or other unknown factors may have reduced the children's ability to process the sentences containing the anomalous words. Results from this study suggest that efforts to characterize auditory processing abilities through electrophysiologic measures may need to examine both group results and individual results if a greater understanding of the underlying neural activity involved in dichotic listening deficits is to be achieved.

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