Behavioral and Electrophysiologic Evidence of Auditory Processing Disorder: A Twin Study

James Jerger*†
Linda Thibodeau†
Jeffrey Martin†
Jyutika Mehta*†
Gail Tillman*†
Ralf Greenwald*†
Lana Britt†
Jack Scott†
Gary Overson†

Abstract
We administered a battery of both behavioral and electrophysiologic measures to a pair of fraternal twin girls, one of whom exhibited symptoms consistent with an auditory processing disorder. Both twins were within normal limits on standardized tests of cognitive and language skills. Basic audiometric measures, as well as behavioral tests of simultaneous masking, backward masking, gap detection, and frequency-sweep discrimination, showed little difference between the twins. Significant differences, however, were evident on event-related potentials (ERPs) in response to both within-channel and across-channel gap detection tasks. Substantial differences were also noted for ERPs to both linguistic and nonlinguistic targets in dichotic listening paradigms. The pattern of electrophysiologic results was consistent with a deficit in the efficiency of interhemispheric transfer of auditory information. A possible reason for the greater effectiveness of electrophysiologic over behavioral measures is discussed.

Key Words: Auditory processing disorder, backward masking, dichotic listening, event-related potential, gap detection, interhemispheric transfer

Abbreviations: APD = auditory processing disorder; CELF-III = Clinical Evaluation of Language Fundamentals-III; CHAPS = Children's Auditory Performance Scale; ERP = event-related potential; GFP = global field power; HINT-C = Hearing in Noise Test for Children; TTC = Token Test for Children; WISC-III = Wechsler Intelligence Scale for Children-III

Sumario
Administramos una batería de pruebas conductuales y electrofisiológicas a un par de niñas gemelas fraternas, una de las cuales exhibía síntomas consistentes con un trastorno de procesamiento auditivo. Ambas gemelas estaban dentro de límites normales para pruebas normadas en cuanto a habilidades cognitivas y del lenguaje. Las mediciones audiométricas básicas, lo mismo que las pruebas conductuales de enmascaramiento simultáneo, de enmascaramiento retrogrado, de detección de brechas, y de discriminación en barrido frecuencial, mostraron poca diferencia entre ellas. Sin embargo, fueron evidentes algunas diferencias significativas en potenciales relacionados con el evento (ERP) en respuesta a tareas de detección de brecha tanto dentro del canal como a través de éste. Se notaron también diferencias sustanciales en los ERP para metas lingüísticas y no lingüísticas en los paradigmas de audición dicótica. El patrón de resultados electrofisiológicos fue consistente con una falta en la eficiencia con que la información auditiva se transfiere entre hemisferios. Se discute aquí una posible razón para explicar la mayor efectividad de las medidas electrofisiológicas sobre las conductuales.

Palabras Clave: Trastorno de procesamiento auditivo, enmascaramiento retrogrado, audición dicótica, potencial relacionado con el evento, detección de brecha, transferencia interhemisférica

Abreviaturas: APD = trastornos de procesamiento auditivo; CELF-III = Evaluación Clínica de Fundamentales del Lenguaje-III; CHAPS = Escala Infantil de Rendimiento del Lenguaje; ERP = potencial relacionado con el evento; GFP = poder global de campo; HINT-C = Prueba de audición en ruido para niños; TTC = Pruebas de fichas para niños; WISC-III = Escala de inteligencia Wechsler para niños-III

*Program in Cognition and Neuroscience and †Program in Communication Sciences, The University of Texas at Dallas, Dallas, Texas
Reprint requests: James Jerger, 2612 Prairie Creek Dr. East, Richardson, TX 75080-2679
During the past 25 years, the diagnosis of auditory processing disorder (APD) in children has been based almost entirely on behavioral measures of performance on specified auditory tasks (Willeford, 1977; Katz, 1982; Keith, 1986; Bellis, 1996). Accumulating evidence suggests, however, that, especially in children, such measures may be influenced to a considerable extent by nonauditory factors, including motivation, distractibility, language skills, intelligence, and cognitive deficits (Mon dor and Bryden, 1991; Cacace and McFarland, 1998; Jerger and Allen, 1998; Chermak et al, 1999; Silman et al, 2000). In view of the success of electroacoustic and electrophysiologic measures in the diagnosis of other auditory disorders (Turner and Nielsen, 1984; Robinette and Facer, 1991; Hood, 1998; Sininger and Starr, 2001), it is reasonable to ask whether such an approach might prove useful in sharpening the diagnosis of APD in children. Such a possibility has been repeatedly suggested by Robert Jirsa and colleagues (Jirsa and Clontz, 1990; Jirsa, 1992, 2001).

When APD is present in one of two twins, either monozygotic or dizygotic, there is an unusual opportunity to evaluate the relative effectiveness of both behavioral and electrophysiologic measures of auditory function in differentiating normal from abnormal performance. Such an opportunity recently presented itself to our laboratory. We were able to carry out extensive testing on a pair of twins, one of whom showed symptoms of impaired listening skills, whereas the other did not. The test battery was chosen in an effort to sample, both behaviorally and electrophysiologically, aspects of auditory function thought to be associated with APD. An additional feature of this case study was the inclusion of a visual control for the auditory evoked potential measures (McFarland and Cacace, 1995).

CASE HISTORIES

The twins are dizygotic girls, aged 10 years, 6 months. One, Twin E (experimental), is reported to suffer persistent academic difficulties characterized by apparent failure in understanding concepts and in remembering complex instructions. She was the first born, by cesarean section, at 31 weeks gestation. The mother reported that, during pregnancy, a sonogram showed the child's head to be somewhat flat on each side. At birth the head was still flat, but within a few weeks was normal in shape. Birth weight was 3 lb, 13 oz. Length was 15¼ inches. The Apgar score was 7 to 9. The child was on oxygen for 5 postnatal days and was discharged after 3 weeks. There was little weight gain between 4 and 6 months, but there were no major health problems at that time. Twin E crawled at 9 months and walked at 15 months. At 17 months, she sustained a febrile seizure that lasted approximately 10 minutes. There have been no subsequent episodes. Talking commenced at about 26 months. Gross motor skills have always been good. She began riding a bicycle without training wheels at age 4. She has been in speech therapy for articulation errors (k/g/l/r) since age 5. The second twin, Twin C (control), has demonstrated none of the problems characterizing Twin E. Her Apgar score was 7 to 8, developmental milestones were normal, and academic achievement has been adequate.

On the Annett Handedness Questionnaire (Annett, 1970), Twin C was strongly right handed (all 12 items right), but Twin E showed a slightly weaker right-sided pattern (8 items right, 3 items left, 1 item either).

Both the mother and the children's teachers completed the Children's Auditory Performance Scale (CHAPS; Smoski et al, 1998) on each twin. For Twin C, scores were in the pass range, according to both the mother and the teacher, in all listening conditions. The total average condition score was +2.5. For Twin E, however, both the mother and the teacher gave at-risk ratings for (1) listening in noise, (2) listening in quiet, (3) memory, and (4) attention. The total average condition score for Twin E was –2.1.

PROCEDURES AND FINDINGS

Testing took place on 3 consecutive days. We addressed cooperation and motivational issues by providing a modest financial award for participation in the study. To describe fully each twin's current level of functioning, a variety of test procedures were administered. They are summarized in Table 1. The following sections detail the test methods and findings on routine audiometric tests, selected behavioral psychoacoustic measures of both peripheral and central auditory processing, standardized cognitive/linguistic evaluations, selected electrophysiologic measures of auditory processing, and a visual electrophysiologic correlate of one auditory processing task.
Table 1  Battery of Tests Administered to Each Twin

<table>
<thead>
<tr>
<th>Tests administered to each twin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic audiometry</td>
</tr>
<tr>
<td>Pure-tone air-conduction audiometry</td>
</tr>
<tr>
<td>Speech audiometry</td>
</tr>
<tr>
<td>Auditory brainstem response</td>
</tr>
<tr>
<td>Transient otocoustic emissions</td>
</tr>
<tr>
<td>Hearing in Noise Test for Children (HINT-C)</td>
</tr>
<tr>
<td>Behavioral psychoacoustic measures</td>
</tr>
<tr>
<td>Simultaneous masking</td>
</tr>
<tr>
<td>Backward masking</td>
</tr>
<tr>
<td>Frequency-sweep discrimination</td>
</tr>
<tr>
<td>Random gap detection test</td>
</tr>
<tr>
<td>Standardized cognitive/linguistic evaluations</td>
</tr>
<tr>
<td>Wechsler Intelligence Scale for Children-III (WISC-III)</td>
</tr>
<tr>
<td>Clinical Evaluation of Language Functions (CELF-III)</td>
</tr>
<tr>
<td>Token Test for Children (TTC)</td>
</tr>
<tr>
<td>Electrophysiologic measures</td>
</tr>
<tr>
<td>Visual gap detection</td>
</tr>
<tr>
<td>Within-channel auditory gap detection</td>
</tr>
<tr>
<td>Across-channel auditory gap detection</td>
</tr>
<tr>
<td>Dichotic listening—acoustic targets</td>
</tr>
<tr>
<td>Dichotic listening—phonemic targets</td>
</tr>
</tbody>
</table>

Basic Audiometry

Standard audiometric procedures were carried out in a sound-treated audiometric booth. Tonal and recorded speech stimuli were presented via a conventional clinical audiometer (Grason-Stadler, GSI 16) routed through standard insert receivers (Etymotic Research, ER-3A). For both twins, pure-tone, air-conduction thresholds were within the normal range (≤ 15 dB HL) at octave intervals from 250 to 8000 Hz. Conventional word recognition in quiet was assessed using traditional, age-appropriate speech materials, phonetically balanced kindergarten (PBK) words. They were presented at two intensity levels (35 dB SL re: spondee threshold and 90 dB HL, respectively). For both twins, performance was well within the normal range (≥ 96%) at both presentation levels, bilaterally.

Sentence recognition was assessed using the Hearing in Noise Test for Children (HINT-C). Sentences were presented adaptively to determine the intensity at which 50 percent correct recognition occurred. Following a practice list, 4 lists of 10 sentences were presented. Sentences were initially presented below threshold and then at increasing levels until they were correctly repeated. Presentation intensity was increased or decreased in 4-dB steps for the first four sentences and in 2-dB steps for the remaining sentences. Threshold was defined as the average intensity necessary for correct recognition of sentences 5 through 10. In this fashion, thresholds for each ear were obtained in quiet and in noise (speech-shaped noise presented at 60 dBA). HINT-C results were similar for both twins. Sentence recognition thresholds ranged from 21 to 23 dBA in quiet and from 60 to 61 dBA in noise. These findings are comparable to the performances of normal-hearing adults on the same task.

Middle ear function was assessed using a GSI-33 Middle-Ear Analyzer. For both twins, tympanograms and ipsilateral acoustic reflexes, screened at 1000 Hz, were normal bilaterally.

Auditory brainstem responses (ABRs) were obtained using the Bio-logic Traveler Express E (Bio-logic Systems Corporation). Alternating rarefaction/condensation clicks were delivered through insert receivers monaurally at 75 dB nHL at a rate of 21.1/sec. The noninverting electrode was placed at CZ, the inverting electrodes at A1 and A2, and the ground at FPZ. The number of artifact-free sweeps averaged was 1024. Responses were analog filtered on-line from 100 to 3000 Hz. All waveforms were replicated. Figure 1 shows ABR waveforms for the left and right ears of both twins. All results, as evidenced by waveform morphologies, peak and interpeak latencies, peak and interpeak amplitudes, and interaural differences, were within normal limits for both twins.

![Figure 1](auditory_brainstem_responses.png)

Figure 1  Auditory brainstem responses of Twins C and E. Average of 1024 alternating polarity clicks presented at 75 dB nHL at a rate of 21.1/sec. All absolute and interpeak latencies were well within normal limits for both twins.
Transient evoked otoacoustic emissions were screened using the Madsen Echo-Screen TE Cochlear Emissions Screener. Both twins passed. Ninety-six percent or higher accepted sweeps were collected in the minimum number of averaging bins.

**Behavioral Psychoacoustic Measures of Auditory Processing**

*Method*

Traditional behavioral measures of APD, such as the Screening Test for Auditory Processing Disorders (SCAN), had been administered previously to Twin E on two separate occasions by other agencies and had not suggested a significant deficit. This led to a search for more novel assessment tools. Behavioral measures finally selected included (1) simultaneous and backward masking, (2) frequency-sweep discrimination, and (3) gap detection. Recent work by Wright and colleagues (1997), Marler and colleagues (2001), and Thibodeau and colleagues (2001) with simultaneous and backward masking paradigms has shown that these measures can be sensitive to APDs in children with language impairments. For an in-depth review of the instrumentation and procedures used in the masking and discrimination tasks, see Thibodeau and colleagues (2001). All auditory stimuli, visual stimuli, and prompts were presented using a Hewlett Packard Pavilion computer and commercial software and hardware by Tucker-Davis Technologies. Stimuli were routed from the D/A converter through an antialiasing filter (low-pass cutoff 8500 Hz), a programmable attenuator, a headphone buffer, and a TDH-39 earphone.

**Simultaneous and Backward Masking.** The probe stimulus for the quiet threshold and masking conditions was a 20-msec, 1000-Hz pure tone, presented monaurally. The masker was a 300-msec, octave-band narrowband noise masker centered at 1000 Hz. The intensity of the masker was held constant at 70 dB SPL. Probe intensity began at 70 dB SPL and then was attenuated with initial and final step sizes of 5 and 2 dB, respectively. Thresholds were determined using an oddity paradigm and a two-down, one-up stepping rule to determine the intensity level at which 71 percent correct identification of the odd interval occurred (Levitt, 1971). Using this approach, trials were presented until 12 reversals were obtained. Threshold was defined as the average intensity level of the final 10 reversals.

**Frequency-Sweep Discrimination.** An adaptive, oddity paradigm was also used for the frequency-sweep discrimination task. The standard stimulus was a 70 dB SPL, 80-msec, 1000-Hz tone, presented monaurally. The variable stimulus was a 70 dB SPL, 80-msec glide from 1000 Hz up to a maximum of 2428 Hz. The probe sweep was adaptively decreased in 500-Hz steps for the first three trials and in 100-Hz steps for the remaining trials.

**Gap Detection.** Gap detection was evaluated using the Random Gap Detection Task recently devised by Robert Keith (2000). Stimuli were presented binaurally at 50 dB HL. During this task, two tones or clicks are presented. The child must say whether one or two stimuli were heard. Stimuli are either frequency pairs at 0.5, 1, 2, and 4 kHz or clicks. Within a run, there are nine pairs of stimuli that are separated by 0- to 40-msec gaps, primarily in 5-msec increments. Based on responses to these pairs, the smallest detectable gap is determined at each frequency.

**Results**

The results for each twin on these various behavioral measures are displayed in Table 2. The values for the quiet and masked thresholds are the average of results obtained on the three different test days.

**Simultaneous and Backward Masking.** There were no significant differences between the twins' performance on the masking tasks. The differences between their thresholds for backward masking and simultaneous masking ranged from 20 to 23 dB across ears, which is comparable to the differences reported for children with normal hearing. There were no appreciable learning effects for simultaneous masked thresholds and only 2- to 6-dB improvement in backward-masked thresholds over the three sessions.

<table>
<thead>
<tr>
<th>Task</th>
<th>Twin E</th>
<th>Twin C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RE</td>
<td>LE</td>
</tr>
<tr>
<td>Threshold in quiet*</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>Masked threshold (simultaneous)*</td>
<td>71</td>
<td>71</td>
</tr>
<tr>
<td>Masked threshold (backward)*</td>
<td>51</td>
<td>48</td>
</tr>
<tr>
<td>Pitch sweep detection (Hz)</td>
<td>1461 1350 1156 1161</td>
<td></td>
</tr>
<tr>
<td>Random gap detection (msec)</td>
<td>6.25</td>
<td>2.75</td>
</tr>
<tr>
<td>Tones</td>
<td>2.00</td>
<td>15.00</td>
</tr>
</tbody>
</table>

*dB SPL.

RE = right ear; LE = left ear.
**Frequency-Sweep Discrimination.** The frequency-sweep thresholds for Twin E were higher (1461 and 1350 Hz for right and left ears, respectively) than for Twin C (1156 and 1161 Hz). There was evidence of learning for this task as both girls' performance improved over the three sessions. Interestingly, the frequency-sweep thresholds for Twin C improved only 183 and 100 Hz for the right and left ears, respectively, whereas for Twin E, thresholds improved 684 and 434 Hz, respectively. However, adequate norms for this task are still lacking.

**Gap Detection.** The smallest detectable gaps for tones and clicks were within the normal range of performance. The gap detection threshold for tones was slightly higher for Twin E (6.25 msec) than for Twin C (2.75 msec). However, the gap detection threshold for clicks was higher for Twin C (15 msec) than for Twin E (2 msec). For both tones and clicks, performance was well within normal limits for both twins.

**Strategy Differences.** Each participant was attentive throughout the sessions. However, there was a noticeable response strategy difference between the girls. Twin E was quick to respond and seemed confident in her choices. Twin C, on the other hand, seemed to deliberate more before selecting her answer. She required more encouragement to guess when the stimuli were below threshold in the tracking procedures. There were no appreciable differences in the standard deviations across runs between the girls. However, on a repeated administration of the random gap detection task, Twin E responded unreliably. Only the results from the first test session are reported.

**Language and Cognitive Testing**

Receptive and expressive language skills were evaluated using the Clinical Evaluation of Language Fundamentals-III (CELF-III; Semel et al, 1995) and the Token Test for Children (TTC). Cognitive function was evaluated using the Wechsler Intelligence Scale for Children-III (WISC-III; Wechsler, 1991). All tests were administered in a single session in a quiet room. The examiner noted, however, that Twin E was distracted by noises outside the room. The twins' performance on these measures was similar to their performance on the auditory behavioral measures. Twin C was hesitant in choosing each response, but Twin E made a rapid election after each stimulus.

Although both girls performed within the normal range, Twin C scored slightly higher than Twin E on all of the language and cognitive measures. Twin E had a receptive language score of 98 and an expressive language score of 96, resulting in a total language score of 96 on the CELF-III. Twin C's scores were 108, 110, and 109, respectively. Both twins demonstrated strengths in comprehending complex verbal directions and short-term recall. Twin E had difficulty formulating sentences when given a word/phrase, determining analogous relationships, and putting together grammatically correct sentences. Twin E's score on the TTC (499) was in the average range compared with Twin C's score (507), which was in the above-average to superior range.

Similarly, Twin E's Full-Scale IQ score on the WISC-III was 92, whereas Twin C's score was 104. Interestingly, both twins showed significant differences between Verbal and Performance scores (Twin E, 24 points; Twin C, 18 points). Both girls exhibited relative strengths in perceptual organization skills and relative weaknesses in verbal comprehension.

Overall, Twin C performed at a slightly higher level than Twin E, but both were well within normal ranges of language and cognitive function.

**Electrophysiologic Measures of Visual and Auditory Processing**

We recorded event-related potentials (ERPs) for one visual (gap detection) and four auditory (within-channel gap detection, across-channel gap detection, dichotic listening for phonemic targets, and dichotic listening for acoustic targets) tasks. The following sections detail the general testing and electrophysiologic recording methods employed and the ERP findings for the visual and auditory tasks.

**Method**

**Delivery of Stimuli.** The children were comfortably seated in a medical examining chair within a sound-treated room. Auditory stimuli were presented at ear level via two loudspeakers positioned at 1.5 meters to either side of the head. Presentation intensity for all auditory stimuli was 55 dB SPL, as read on a sound level meter (C scale) positioned at the location of the participant's head during testing. Visual stimuli were presented on a 38-cm computer screen centered at 2.2 meters in front of the child. Both behavioral and electrophysiologic data were collected simultaneously using a basic "oddball"
In this scheme, participants see or hear a train of two kinds of stimuli, a frequent or nontarget event, which occurs on the majority of presentation or trials, and a rare or target event, which occurs on a relatively smaller percentage of trials. The twins indicated their responses using two buttons, labeled “yes” and “no” and vertically positioned in front of them. Instructions were verbally given to each twin prior to each task along with a brief practice session to ensure that they understood the directions. In the visual task, stimuli were repeated with an intersignal interval of 1.6 sec. In all auditory tasks, the next trial was initiated by the child’s response to the previous trial.

**Electrophysiologic Recording Techniques.** ERPs were collected using the Neuroscan electrophysiologic data acquisition system (SCAN 4.2, Neurosoft, Inc.). Continuous electroencephalographic activity (EEG) was recorded from 32 silver-silver chloride electrodes mounted in an elastic cap (Neurosoft) affixed to the scalp according to the International 10-20 system (Jasper, 1958). Electrode impedances were always less than 5 kohms. Eye movements and eye blinks were monitored via electrodes placed above and at the outer canthus of the left eye. EEG channels were referenced to linked mastoid electrodes with a forehead electrode as ground. Ongoing EEG activity was sampled at 1000 Hz, amplified, analog filtered from 0.15 to 70 Hz (except 1.0–100 Hz for the eye channel), digitized, and stored for off-line analysis. Off-line, individual epochs, encompassing −200 to 1800 msec relative to stimulus onset, were derived. Epochs were rejected if the activity in the eye channel exceeded ± 50 µV. Following artifact rejection, epochs were separately averaged for target and nontarget stimuli. Only epochs corresponding to correct behavioral responses were averaged. Overall, the number of acceptable sweeps ranged from 20 to 60 for Twin C and from 20 to 78 for Twin E. The average number of acceptable sweeps was 31 for Twin C and 40 for Twin E. Successfully averaged evoked potential waveforms were then linearly detrended, baseline corrected relative to the 200-msec prestimulus interval, and digitally low-passed filtered at 20 Hz (−48 dB/octave).

ERP topographies were constructed by interpolation of voltages between neighboring electrodes. Bivalent colors (blue and red) representing the range of observed voltages were then assigned. All maps were scaled such that only positive voltages are displayed. Thus, the deepest shade of blue represents baseline activity. Increasing positivity is coded by decreasing shades of blue and increasing shades of red. All maps are as if viewed from above with the nose at the top of the map and right and left hemispheres to the right and left of midline, respectively.

To derive, from the various electrodes, a single measure of peak latency to generate the topographic maps, an individual global field power (GFP) waveform (Skrandies, 1989, 1990) was computed. The GFP transform provides an objective method for choosing the latency at which to generate maps because it examines the extent to which the electrical activity across the entire surface of the scalp is nonuniform and the latency at which maximal nonuniformity occurs.

Finally, all subsequent analyses are confined to the waveforms and activation patterns in response to targets only.

**Visual Gap Detection.** We addressed the issue of modality specificity by including a visual control condition. Our reasoning was that, if the twins differed on both visual and auditory tasks, this would contraindicate a modality-specific disorder (e.g., APD). Conversely, if the twins were similar on the visual task but differed on the auditory tasks, this would support an auditory-specific deficit.

For the visual control condition, we developed a simple visual gap detection task. Each twin was asked to view the center of the computer screen. A single white circle, 8 cm in diameter, was presented on a black background every 1.6 sec. The duration of the circle was 900 msec and was presented either continuously (nontarget) or with a temporal gap (target). The gap lasted either 200 or 400 msec and always occurred midway relative to the total duration. Over a total of 400 trials, half of the presentations were randomly presented targets (25% for each gap duration). Figure 2 illustrates the appearance of the white circle on the computer screen and the time course of the two temporal gaps. The twins were asked to indicate via the response pad whether the circle contained a temporal gap. Evoked potentials were then separately averaged for target and nontarget stimuli. Since preliminary analysis showed no obvious difference between results for the two gap sizes in either twin, data were collapsed across this dimension. The trigger signaling the onset of each epoch was set at the initial onset of the white circle.

**Auditory Gap Detection.** Two different procedures for assessing auditory gap detection
Visual Gap Detection

Monitor Screen Display

Figure 2 Schematic illustration of white circle stimulus and its time course in the visual gap detection paradigm.

were employed, “within-channel” and “across-channel” paradigms (Phillips et al. 1997; Phillips, 1999). The stimuli used in both conditions consisted of broadband noise, created digitally at a sampling rate of 22,050 Hz with 16-bit amplitude resolution, using the Cool Edit Pro software. The twins were asked to respond to target and nontarget stimuli presented in an oddball paradigm as previously described.

In the within-channel gap detection procedure, the nontarget stimulus was a noise burst, 500 msec in duration, with a 5-msec rise-decay time. It was presented simultaneously from both the right and left loudspeakers such that the participant perceived a single noise burst centered above the head. Care was taken to ensure that the loudspeakers operated in phase. The target feature consisted of a 10-msec silent gap centered within both noise bursts. The total number of trials was 200. The target feature was presented on 25 percent of trials. Evoked potentials were then averaged separately to target and nontarget stimuli. The trigger signaling the onset of each epoch was set at the onset of the gap.

**Dichotic Listening Tasks.** In the dichotic listening tasks, pairs of monosyllabic consonant-vowel-consonant (CVC) words were presented simultaneously (i.e., in the dichotic mode) to the participants in an “oddball” paradigm. Words were recorded in a sound-treated room by an adult male, monolingual speaker of English. Speech was sampled at a rate of 22,050 Hz with 16-bit amplitude resolution using the Cool Edit Pro software. Overall intensities of the words were equated based on their average root mean square amplitudes. The words were then divided into two broad categories, targets and nontargets. For a nontarget event, 2 of a list of 24 nontarget words constituting a dichotic pair were selected at random and were without further relevance. For a target event, the dichotic pair contained a nontarget word and a word containing a predefined target feature.

In the present study, two target features were evaluated, acoustic and phonemic. We selected the phonemic feature as a linguistic or left-hemisphere-specialized task and the acoustic feature as a nonlinguistic or right-hemisphere-specialized task. The predefined acoustic target feature was a 500-msec burst of sawtooth noise (f0 = 120 Hz). The predefined phonemic target was any word that rhymed with “jet” (e.g., “met,” “set,” “get”). The duration of the acoustic target was similar to the mean duration of both the nontarget words (502 msec) and the phonemic targets (496 msec).

Two test conditions were subsequently devised, one involving acoustic targets and one involving phonemic targets. Each condition contained a total of 320 trials. For both conditions, the nontarget event occurred on 70 percent of trials and the target event on 30 percent of trials. Thus, target stimuli were randomly presented to each ear on 15 percent of trials, with the constraint that target events could not occur more
than twice in succession. The children were asked to respond to target and nontarget events as previously described. Evoked potentials were then averaged separately to target and nontarget stimuli. In all dichotic conditions, the trigger signaling the onset of each epoch was set at the onset of the word.

**Results**

**Detectability Indices.** Hit rates and false alarm rates of behavioral responses in each of the ERP paradigms were converted to the non-parametric detectability index, A', the area under the receiver operating characteristic curve corresponding to the d' value derived from hit rate and false alarm rate (Turner and Nielsen, 1984). These indices are summarized in Table 3 for all ERP conditions. They show that behavioral performance scores on the various oddball tasks were at a relatively high level for both twins in all conditions.

**Visual Gap Detection.** Figure 3 compares the two twins in the visual control condition. The upper panel compares waveforms at the CPZ electrode site. There was an early response to stimulus onset in the 200- to 300-msec range, followed by a late positive component in the latency region from 700 to 800 msec. This late positivity is customarily labeled the P3 peak. The lower panels compare scalp topography of the P3 peak in the latter range. In this figure, and all subsequent figures, the exact latency at which topography was mapped was based on the positive peak of the GFP waveform for that condition. Overall, these results show that, on a visual task involving a temporal gap, the electrophysiologic responses of the two twins were comparable.

**Within-Channel Auditory Gap Detection.** Figure 4 compares the two twins in the within-channel gap detection condition. The upper panel compares waveforms at the C4 electrode for Twin C and at the TP7 electrode for Twin E. In the case of Twin C, there was an early response to stimulus onset in the 50- to 150-msec range, followed by a P3 peak in the latency region from 700 to 800 msec. This late positivity is customarily labeled the P3 peak. The lower panels compare scalp topography of the P3 peak in the latter range. In this figure, and all subsequent figures, the exact latency at which topography was mapped was based on the positive peak of the GFP waveform for that condition. Overall, these results show that, on a visual task involving a temporal gap, the electrophysiologic responses of the two twins were comparable.

**Across-Channel Auditory Gap Detection.** Figure 5 compares the two twins in the across-channel gap detection condition when the stimulus began on the left side and ended on the right side. The upper panel compares waveforms at the C4 electrode for both twins. In the case of Twin C, the waveform peaked in the latency region from 900 to 1100 msec. In the case of Twin E, however, the P3 peak was considerably attenuated in this latency range. The lower panels compare scalp topographies in the 900- to 1100-msec range. Twin C showed activation over both hemispheres, with slightly greater activation over the right hemisphere. Twin E, however, showed, on this comparable amplitude scaling, only a limited activation pattern in the temporoparietal region on the left side. The difference in activation patterns is striking.

**Dichotic Listening—Phonemic Feature.** Figure 7 compares the twins on the dichotic listening task when the phonemic feature (words that rhyme with “jet”) was presented from the left side. The waveform for Twin C was taken at the CPZ electrode and the waveform for Twin E at the P4 electrode. Again, the ERP, in the latency region from 600 to 1200 msec, was more robust for Twin C than for Twin E. The topographic maps in the lower panel, taken in the 800- to 900-msec range, showed substantially

<table>
<thead>
<tr>
<th>Measure</th>
<th>Twin E</th>
<th>Twin C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual gap detection</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Within-channel gap detection</td>
<td>0.97</td>
<td>0.99</td>
</tr>
<tr>
<td>Across-channel gap detection (R-L)</td>
<td>0.98</td>
<td>0.99</td>
</tr>
<tr>
<td>Across-channel gap detection (L-R)</td>
<td>0.96</td>
<td>0.99</td>
</tr>
<tr>
<td>Dichotic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acoustic feature (target-R)</td>
<td>0.97</td>
<td>0.99</td>
</tr>
<tr>
<td>Acoustic feature (target-L)</td>
<td>0.97</td>
<td>0.99</td>
</tr>
<tr>
<td>Phonemic feature (target-R)</td>
<td>0.72</td>
<td>0.99</td>
</tr>
<tr>
<td>Phonemic feature (target-L)</td>
<td>0.72</td>
<td>0.90</td>
</tr>
</tbody>
</table>

R = right; L = left.
Figure 3  Visual gap detection. *Upper panel* compares event-related potential (ERP) waveforms at electrode CPZ. *Lower panel* compares topographic activation patterns at the P3 peak of the ERP waveform. View is from above. Right hemisphere on right, left hemisphere on left. Note similarity between Twins E and C.

greater activation for Twin C than for Twin E. In addition, it is noteworthy that the activation pattern was asymmetric to the left of midline for Twin C but to the right of midline for Twin E.

Figure 8 shows results for the analogous task when the phonemic target was directed to the right side. Again, the waveforms (at CP3 for Twin C and at CP4 for Twin E) showed greater P3 amplitude in the region from 800 to 900 msec for Twin C than for Twin E, and, again, the activation pattern was to the left of midline for Twin C and to the right of midline for Twin E.
Dichotic Listening—Acoustic Feature.
Figure 9 compares the twins on the dichotic listening task when the acoustic feature (sawtooth noise) was presented from the left side. The waveforms were taken at CP4 and CP3 for Twin C and Twin E, respectively. Here the P3 peak amplitude was observed in the 500- to 800-msec range in both twins. Peak amplitudes were similar. And, again, it is noteworthy that, in this condition, the activation pattern was asymmetric to the right of midline for Twin C but to the left of midline for Twin E.

Figure 10 compares the twins on the dichotic listening task when the acoustic feature was
Figure 5  Across-channel auditory gap detection. First noise burst to left side, second noise burst to right side. Upper panel compares waveforms at electrode C4 for both twins. Lower panel compares activation patterns at the peak amplitude of the global field power waveform. Twin C shows a robust pattern of activation over both hemispheres but greater activity over the right hemisphere. On the same amplitude scale, Twin E shows little activity over either hemisphere.

presented from the right side. The waveforms were taken at P4 and P3 for Twin C and Twin E, respectively. Again, the P3 peak, in the latency region from 600 to 800 msec, was more robust for Twin C than for Twin E. The topographic maps in the lower panel showed substantially greater activation for Twin C than for Twin E. Note also that the activation pattern was asymmetric to the right of midline for Twin C but to the left of midline for Twin E.

In Figures 11 and 12, the topographic maps for both twins in the phonemic and acoustic dichotic tasks have been replotted to facilitate comparison among the four conditions. In addition, the maps for the acoustic targets have been rescaled to normalize for absolute amplitude dif-
Figure 6  Across-channel auditory gap detection. First noise burst to right side, second noise burst to left side. Upper panel compares waveforms at electrode C4 for both twins. Lower panel compares activation patterns at the peak amplitude of the global field power waveform. Again, Twin C shows a robust pattern of activation over both hemispheres but greater activity over the right hemisphere. On the same amplitude scale, Twin E shows greatly attenuated activity over both hemispheres but slightly greater activity over the right hemisphere.

Differences between the two twins in the two conditions. In the case of Twin C (see Fig. 11), there was little difference between activation patterns for right-sided and left-sided targets in either the acoustic or phonemic conditions. In addition, activation patterns were asymmetric to the right hemisphere for the acoustic feature and to the left hemisphere for the phonemic feature. For Twin C, there was substantial hemispheric asymmetry but little interaural asymmetry.

In contrast, results for Twin E (see Fig. 12) show a distinct pattern of interaural asym-
Figure 7  Dichotic listening. Phonemic target to left side. Upper panel compares waveforms at electrode CPZ for Twin C and at electrode P4 for Twin E. Lower panel compares activation patterns at the peak amplitude of the global field power waveform. Twin C shows a robust pattern of activation over both hemispheres but slightly asymmetric to the left hemisphere. On the same amplitude scale, Twin E shows greatly attenuated activity, slightly to right of midline.

metry. When the to-be-attended feature was acoustic, the activation pattern was greater for left-sided targets than for right-sided targets. But when the to-be-attended feature was phonemic, the activation pattern was greater for right-sided than for left-sided targets. In other words, Twin E showed a distinct left-sided disadvantage for linguistic processing and a right-sided disadvantage for nonlinguistic processing. Note also that activation patterns were asymmetric to the left of midline in the acoustic condition but asymmetric to the right of midline in the phonemic condition. The directions of these hemispheric asymme-
Figure 8  Dichotic listening. Phonemic target to right side. Upper panel compares waveforms at electrode CP3 for Twin C and at electrode CP4 for Twin E. Lower panel compares activation patterns at the peak amplitude of the global field power waveform. Twin C shows a robust pattern of activation over both hemispheres but asymmetric to the left hemisphere. On the same amplitude scale, Twin E shows greatly attenuated activity, slightly to the right of midline.

tries were exactly opposite to those shown by Twin C.

ERP Reliability. It is relevant to ask to what extent the topographic maps derived from ERP waveforms were repeatable in the two twins. To illustrate reliability, we selected a single test condition, acoustic target left. From the set of epochs corresponding to correct responses to targets in this condition we formed two subsets of equal size. Epochs from the original set were randomly assigned to one of these two subsets. For each twin, 40 epochs were randomly divided into two 20-epoch subsets. Topographic maps at the latency corresponding to the maximal peak of the GFP waveform were then constructed for each subset of epochs. Figure 13 shows the
results. In both twins, the maps derived were reasonably equivalent. Figure 14 shows the averaged eye-channel activity corresponding to each of these topographic maps. Across the entire recording epoch, the eye activity is less than ±2 µV. Thus, ERP results were not confounded by excessive eye artifact.

**Latencies.** In the case of the gap detection conditions, latency was measured from the onset of the gap. For the dichotic word conditions, latency was measured from the onset of the word. Latencies thus defined for each twin are summarized in Table 4. Results are essentially comparable for each twin. Both
Figure 10  Dichotic listening. Acoustic target to right side. Upper panel compares waveforms at electrode CP4 for Twin C and at electrode P3 for Twin E. Lower panel compares activation patterns at the peak amplitude of the global field power waveform. Twin C shows a robust pattern of activation over both hemispheres but asymmetric to the right hemisphere. On the same amplitude scale, Twin E shows greatly attenuated activity, to the left of midline.

showed latencies in the 700- to 1100-msec range for gap detection tasks and in the 600- to 880-msec range for dichotic tasks. Although Twin E tended to have shorter latencies than Twin C, differences were not consistent across conditions.

DISCUSSION

Does Twin E Have APD?

There is ample evidence that Twin E fits the expected profile of a child with an auditory-
Figure 11  Activation patterns for Twin C on all four dichotic listening conditions. Scaling has been adjusted to equate peak amplitudes between acoustic and phonemic conditions. Note similarity of activation patterns for acoustic targets, whether to right or left side, and similarity of activation patterns for phonemic targets, whether to right or left side. Note also that hemispheric asymmetry is to the right of midline for acoustic targets and to the left of midline for phonemic targets.

specific processing disorder. The following findings are relevant:

1. Basic audiometric measures were within the normal range.

2. On the CHAPS, the ratings of both the mother and the classroom teacher were consistent with a child who is a poor listener, especially in difficult listening situations.
Figure 12  Activation patterns for Twin E on all four dichotic listening conditions. Scaling has been adjusted to normalize peak amplitudes between acoustic and phonemic conditions. Note greater activation for acoustic targets to left side than to right side and greater activation for phonemic targets to right side than to left side. Note also that hemispheric asymmetry is to the left of midline for acoustic targets and to the right of midline for the phonemic targets. This is a reversal of the hemispheric asymmetry observed for Twin C.

3. Normal otoacoustic emission measures effectively ruled out a deficit in the auditory periphery.

4. The presence of normal ABRs effectively ruled out auditory dys-synchrony (formerly auditory neuropathy) as an explanation for the problem.

5. Cognition was in the normal range.

6. Language was in the normal range.
Figure 13  Repeatability of map topography for each twin in the dichotic acoustic target condition. For Twin E, the original set of 72 epochs corresponding to correct responses was randomly divided into two 36-epoch subsets. For Twin C, the original set of 40 epochs was randomly divided into two 20-epoch subsets.

7. There was ample evidence of abnormalities in brain activation patterns on a number of auditory tasks, including
   a. Within-channel gap detection
   b. Across-channel gap detection
   c. Dichotic listening for a linguistic target
   d. Dichotic listening for a nonlinguistic target

8. These deficits appeared to be auditory specific, as evidenced by comparable brain activation patterns in the visual control condition (McFarland and Cacace, 1995).

It should be emphasized that this conclusion is reached, not on the basis of poor performance on auditory tasks alone, but on the
overall profile of results. The addition of cognitive measures, linguistic measures, and the visual control condition makes it possible to rule out the principal nonauditory explanations for the auditory findings. Similarly, the ABR and otoacoustic emissions are essential to rule out auditory dys-synchrony.

**Can We Discern a Basis for the Auditory Problem?**

**Interaural Asymmetries**

The pattern of dichotic listening results for Twin E suggests a deficit in the interhemispheric
transfer of auditory information via the corpus callosum. When the to-be-attended feature was phonemic (i.e., linguistic), there was a decided interaural asymmetry favoring the right ear. But when the to-be-attended feature was acoustic (i.e., nonlinguistic), interaural asymmetry favored the left ear. Such a reversal of interaural asymmetry by simply changing the to-be-attended feature is perhaps best explained by loss in the efficiency of interhemispheric transfer via the corpus callosum. We may conjecture that, when the target is linguistic, the right ear enjoys privileged direct access to the left hemisphere, but the left ear, already at a disadvantage because its input must be relayed to the left hemisphere via the corpus callosum, is further penalized by loss in the efficiency of interhemispheric transfer. When the target is nonlinguistic, the situation is reversed. Now the left ear enjoys direct, privileged access to the right hemisphere, and the right ear, already at a slight disadvantage, is further penalized by loss in the efficiency of interhemispheric transfer. Such a scenario is based, of course, on well-established evidence (Hellige, 1993) that the left hemisphere is specialized for certain aspects of linguistic processing (e.g., phonemic features), whereas the right ear is specialized for certain aspects of nonlinguistic processing (e.g., acoustic features). Patterns of auditory test results similar to those observed in Twin E have been described in children with delayed maturation of the corpus callosum (Musiek et al., 1984). The authors labeled this the “auditory disconnection profile.” Similar findings have been described in some elderly persons (Jerger et al., 1995, 2000).

### Hemispheric Asymmetries

In addition to these reversing interaural asymmetries, there was consistent evidence, in Twin E, of reversed hemispheric asymmetry. Whereas Twin C showed greater activation over the left hemisphere for linguistic processing and greater activation over the right hemisphere for nonlinguistic processing, Twin E showed a reversal of both asymmetries. Activation was greater over the right hemisphere for linguistic processing and greater over the left hemisphere for nonlinguistic processing. Although it is possible that differences in handedness preference between the twins might account for this reversal, both twins would be categorized as right handed (12 of 12 items for Twin C, 8 of 12 items for Twin E), rendering such an interpretation unlikely. Moreover, a number of investigators (Banich and Belger, 1990; Banich et al., 1990; Clarke, 1990) have shown that, at least in the visual modality, interhemispheric communication and coordination are not related to handedness. For a thorough review of these issues, see Hellige (1993).

The possibility that lack of appropriate hemispheric lateralization may underlie disordered function has been studied extensively in a number of childhood disorders. Evidence of reversal in appropriate hemispheric asymmetry has been found in children with dyslexia, learning disability, and language disorders. For a more detailed review of these findings, see Estes and colleagues (2002).

### Basis for ERP Amplitude Reduction

A model of ERP elicitation has been provided by Kok (2001). Assuming that the event categorization process reflected in ERP amplitude is accomplished by comparing the external stimulus with an internal representation, he proposed that three major amplitude determinants, stimulus probability, task relevance or emphasis, and task difficulty, interact with attention and working memory to determine ultimate amplitude. Low probability and high relevance act to increase amplitude, whereas increasing task difficulty acts to decrease amplitude. One factor affecting task difficulty is assumed to be a perceptually impoverished stimulus. We suggest that, in the case of Twin E, satisfactory behavioral performance could be achieved in spite of degraded input, but the additional attentional and memory resources required to overcome the increased task difficulty were reflected in the attenuated ERP amplitude. That Twin E may have had problems in the allocation of attentional resources is supported by the observation, noted earlier, of strategy differences in their approaches to the listening tasks. Twin C
typically deliberated carefully before responding, but Twin E was usually quick to respond with little evidence of deliberation.

**How Did Behavioral Tests Fare?**

Not very well. On the behavioral tests we administered, there was little to differentiate the two twins. Routine speech audiometric measures, HINT-C scores, simultaneous masking, backward masking, and the random gap detection test failed to differentiate the twins. On the frequency-sweep discrimination test, the performance of Twin E was noticeably poorer than that of Twin C, but limited normative data make this finding difficult to interpret.

Overall, it is difficult to escape the conclusion that electrophysiologic measures highlighted Twin E's deficits more effectively than behavioral measures. It may be relevant to observe, in this regard, that the two approaches, at least in the present study, ask two somewhat different kinds of questions. The behavioral measures tend to ask threshold questions and accuracy questions. What is the smallest gap that you can detect? What is the smallest frequency sweep that you can detect? What is your masked threshold in the presence of simultaneous or delayed noise? How accurately can you recognize words and sentences that have been filtered or masked?

In contrast, the procedures necessary to evoke ERPs purposely avoid asking this genre of questions. They ask, instead, what are the brain activation patterns when you are performing a task specifically designed to produce relatively high accuracy scores? What are the brain activation patterns when you are performing successfully? To emphasize this aspect of processing, for example, only epochs corresponding to correct behavioral responses are analyzed.

Consider the case of within-channel gap detection. The behavioral test (random gap detection test) asks, "What is the smallest gap that you can detect?" The assumption is that this will be in proportion to your difficulty in analyzing small temporal intervals in real life. But in the ERP within-channel gap detection procedure, we present an easily discerned gap and ask,"What is the brain activation pattern in response to its detection?" The interest here is not in what happens when you cannot detect the gap but in what happens when you can detect it. The effort is to seek brain correlates associated with the actual processing of auditory events rather than to dwell on what is not being processed. In this context, the behavioral measure of gap detection threshold failed to distinguish the twins, but the electrophysiologic measure of within-channel gap detection showed a marked difference in brain activation patterns.

Similarly in the dichotic tasks, we ask not how well you can repeat back two different words presented dichotically, but what the brain activation patterns are when you correctly identify a target word on one side in the presence of contralateral competition from the other side.

It is possible that answers to this genre of question provide a more meaningful assessment of listening difficulties in everyday life than answers to questions about thresholds and accuracy scores.

**SUMMARY**

Comparison of Twin C and Twin E on a broad battery of both behavioral and electrophysiologic measures suggested that Twin E suffered from an auditory-specific perceptual deficit. ERPs in both gap detection and dichotic paradigms were particularly effective in identifying the disorder. The pattern of abnormal ERP findings in the dichotic paradigms suggested a deficit in the interhemispheric transfer of auditory information. A possible reason for the greater effectiveness of electrophysiologic over behavioral measures was considered.

**Acknowledgment.** We are grateful to Robert Chesnut, Audio Electronics, and Wendy Crumley, Biologic Instruments, for generous assistance with electronic instrumentation.

**REFERENCES**


