Clinical Forum

Central Auditory Processing Disorder: A Case Study

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Abstract

We carried out extensive audiologic, electrophysiologic, and neuropsychologic testing on a young woman who complained that she had difficulty hearing in her educational environment. Conventional audiometric results, including pure-tone, speech, and immittance audiometry, were all within normal limits. The subject performed normally on tests involving the processing of rapidly changing temporal information, interaural time and intensity difference detection, and both absolute and relative sound localization. Early, middle, late and task-related auditory evoked potentials were essentially normal, although some asymmetry was observed in the middle latency (MLR) and late (LVR) responses. There was, however, a consistent left-ear deficit on dichotic sentence identification, on threshold and suprathreshold speech measures in the left sound field when various types of competition were delivered in the right sound field, and on cued-target identification in the left sound field in the presence of multitalker babble. Results suggest a central auditory processing disorder characterized by an asymmetric problem in the processing of binaural, noncoherent signals in auditory space. When auditory space was structured such that the target was directed to the left ear, and the competition to the right ear, unwanted background was less successfully suppressed than when the physical arrangement was reversed.

Key Words: Central auditory processing disorder, auditory-perceptual disorders, auditory-diseases-central, auditory evoked potentials

The concept of central auditory processing disorder (CAPD) in children arose from observations by teachers and parents that some children appear to have difficulty in hearing even though their pure-tone audiograms indicate normal peripheral sensitivity. Observers have described problems in hearing the teacher in the presence of background noise, in executing a sequence of auditory instructions and commands, and in sustaining attention to auditory input (Cohen, 1980; Keith, 1981; Lasky, 1983; Willeford, 1985). The common thread in this “symptom complex” is the consistent description of a child who appears to have a “hearing loss,” especially in the classroom situation, but whose pure-tone audiogram is invariably within normal limits (Cohen, 1980; Gerber and Mencher, 1980; Jerger et al, 1988; Musiek and Guerkink, 1980; Rampp, 1979; Willeford, 1985).

The construct that such problems may be related to dysfunction in the central auditory system follows from the rich literature on the
behavioral manifestations of documented brain lesions affecting the central auditory pathways and centers (cf., Calearo and Antonelli, 1968; Berlin et al, 1972; Liden and Korsan-Bengsten, 1973; Jerger, 1960; Jerger and Jerger, 1974, 1975; Lynn et al, 1972; Speaks et al, 1975). Patients with demyelinating disease, intra-axial tumor, or cerebrovascular insult typically show a similar symptom complex if the brain lesion affects the central auditory system. Peripheral hearing sensitivity, as indicated by the pure-tone audiogram, is within normal limits, but the ability to process suprathreshold auditory signals may be mildly to severely compromised, especially in the presence of competing background sounds. This similarity in symptomatology invites speculation that at least some of the apparent auditory problems observed in children without known brain lesions may be manifestations of as-yet-undetected dysfunction of the central auditory system (Barr, 1972; Gerber and Mencher, 1980; Jerger et al, 1988; Musiek et al, 1984).

Complicating the issue, however, is the fact that the combination of apparent auditory processing disorder and academic difficulty has also invited speculation, among educators, that at least some of the problems subsumed under the rubric of "learning disorder" or "learning disability" may be due to such auditory deficits (cf., Beasley and Freeman, 1977; Katz and Illmer, 1972; Keith, 1981; Knox and Roeser, 1980; Rampp, 1979; Sloan, 1980). Similarly, the frequently observed association between receptive and expressive language function has invited speculation that at least some of the language disorders of children may be attributed to CAPD (cf., Lubert, 1981; Sloan, 1980; Tallal, 1980; Tallal et al, 1985a, b). In the absence of substantial experimentally-controlled data such speculation has invited counter speculation challenging the reality of the phenomenon of a specifically-auditory processing disorder (Bloom and Lahey, 1978; Lyon, 1977; Rees, 1973, 1981). The association, for example, between attentional deficits and performance on auditory tests (cf., Campbell and McNeil, 1985; Gascon et al, 1986) has suggested to some investigators that the presumed auditory problem may, in fact, be a manifestation of impaired attention (DeMarco et al, 1989; Robin et al, 1989).

In the present paper we present a considerable body of data from a single subject with what we believe to be an auditory-specific central processing disorder. This young woman complained of hearing and understanding difficulties in her educational environment. She felt that her problems were sufficient to consider use of a hearing aid. Basic audiologic measures, including pure tone audiometry, acoustic immittance measures, and routine speech audiometry were all within normal limits. We noted on routine examination, however, an abnormality in dichotic listening; specifically, a left ear deficit on the Dichotic Sentence Identification (DSI) test and set out to explore the nature of this apparent deficit in greater detail. We believe that our findings address many of the persistent issues surrounding the controversial area of CAPD.

DESCRIPTION OF SUBJECT

History

The subject was an 18-year-old woman who complained that, for the past 2 years, she had experienced difficulty in hearing and understanding her high-school teachers. She complained that she frequently missed the teacher's verbal assignments. The most difficulty was experienced when the classroom was noisy. She did not complain of hearing loss in the sense of reduced sensitivity to sound. Rather, she described her problem as a difficulty in understanding the teacher when there was interference from background noise. She had no problem with the telephone on the right ear but reported that the sound was "not as good" when listening on the left ear. She felt that her problems were sufficient to consider use of a hearing aid.

On the Self Assessment of Communication (SAC) scale she scored 38 percent, a value associated with mild auditory handicap (Schow and Tannahill, 1977). She reported particular difficulty on question 3 ("Do you experience communication difficulties while listening to someone speak to a large group?") and question 5 ("Do you experience communication difficulties when you are in an unfavorable listening environment?"). Nevertheless she had just graduated from high school without obvious academic difficulty and was college-bound as a music major.
Physical Findings

Physical examination revealed an alert, well-developed, young adult. Both external auditory canals and tympanic membranes were normal. There was no evidence of pathology in the middle ear clefts. Extraocular muscle movements were normal. Pupils were equally round and reactive to light and accommodation. Nasal cavity, oral cavity, pharynx, and larynx were normal. Neck findings were negative. Cranial nerves III to XII were intact.

Routine laboratory studies included a normal complete blood count with normal sedimentation rate. Serum T4 and T3 levels as well as T3 uptake level were normal. Urinalysis was negative. Five-hour glucose tolerance test was normal. A magnetic resonance image (MRI) of the brain and posterior fossa was performed with the administration of gadolinium. No abnormalities were observed in the brain or in the region of the VIII nerve complex.

Basic Audiometric Evaluation

Figure 1 shows routine pure-tone and speech audiometric data. With the exception of the threshold at 250 Hz in the right ear (25 dB HL), all pure-tone thresholds were within normal limits. The PTA (average of pure-tone threshold hearing levels at 500, 1000, and 2000 Hz) was 12 dB HL for the right ear and 10 dB HL for the left ear. Results of basic speech audiometry were also within normal limits. The threshold for spondee words was 20 dB HL in each ear, the PB score at 80 dB HL was 96 percent in the left ear, 90 percent in the right ear, and the maximum of the performance versus intensity (PI) function for SSI sentences at 0 dB MCR function was 90 percent in the right ear and 100 percent in the left ear. Immittance audiometry showed a normal, type A, tympanogram in each ear, and acoustic reflex thresholds, both crossed and uncrossed, varied from 90-95 dB HL across the frequency range from 500 to 4000 Hz.

The masking level difference (MLD) for a 500-Hz pure tone in the presence of broad-band noise was 16 dB, well within the normal range. On the routine DSI test, however, the subject scored 97 percent on the right ear but only 79 percent on the left ear. This 18 percent interaural difference exceeds the normal boundary of 16 percent established by Fifer et al (1983).

Figure 1  Pure-tone and speech audiometric findings in an 18-year-old woman who complained that she had difficulty hearing her high-school teachers.

NEUROPSYCHOLOGIC EXAMINATION

The subject underwent a neuropsychologic evaluation, including tests of cognitive, perceptual, perceptual-motor, simple and choice reaction times, and other neurobehavioral abilities. The evaluation, described in previous communications (Jerger et al, 1989), was administered and interpreted by a neuropsychologist. Findings are summarized in Tables 1 and 2. Table 1 shows scores on the various subtests of the Wechsler Adult Intelligence Scale (WAIS), the Wechsler Memory Scale, the Boston Naming Test, and the Spatial Orientation Memory Test. Table 2 lists simple auditory, simple visual, and 4-choice visual reaction times.

The profile of neuropsychologic abilities in this patient was remarkable for evidence of:

1. supranormal global intelligence
2. supranormal speed of mental processing
3. supranormal visual-spatial organizational abilities
4. supranormal higher cognitive abilities, including vocabulary and verbal similarities
5. discrepancy between global intelligence and fund of knowledge (information).
Table 1 Performance Scores of Experimental Subject on Selected Cognitive Measures

<table>
<thead>
<tr>
<th>Cognitive Measure</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>WAIS-R: Verbal Tests*</td>
<td></td>
</tr>
<tr>
<td>Information</td>
<td>8</td>
</tr>
<tr>
<td>Vocabulary</td>
<td>13</td>
</tr>
<tr>
<td>Arithmetic</td>
<td>8</td>
</tr>
<tr>
<td>Comprehension</td>
<td>12</td>
</tr>
<tr>
<td>Similarities</td>
<td>17</td>
</tr>
<tr>
<td>Digit span</td>
<td>11</td>
</tr>
<tr>
<td>WAIS-R: Performance Tests*</td>
<td></td>
</tr>
<tr>
<td>Picture completion</td>
<td>13</td>
</tr>
<tr>
<td>Picture arrangement</td>
<td>12</td>
</tr>
<tr>
<td>Block design</td>
<td>13</td>
</tr>
<tr>
<td>Object assembly</td>
<td>13</td>
</tr>
<tr>
<td>Digit symbol</td>
<td>13</td>
</tr>
<tr>
<td>WAIS-R: Summary</td>
<td></td>
</tr>
<tr>
<td>Verbal IQ</td>
<td>105</td>
</tr>
<tr>
<td>Performance IQ</td>
<td>120</td>
</tr>
<tr>
<td>Full scale IQ</td>
<td>112</td>
</tr>
<tr>
<td>Wechsler Memory Scale†</td>
<td></td>
</tr>
<tr>
<td>Passages</td>
<td>9.5</td>
</tr>
<tr>
<td>Visual reproduction</td>
<td>13</td>
</tr>
<tr>
<td>Associative learning</td>
<td>21</td>
</tr>
<tr>
<td>Boston Naming Test†</td>
<td>57</td>
</tr>
<tr>
<td>Spatial Orientation Memory†</td>
<td>14</td>
</tr>
</tbody>
</table>

*age-corrected scores
†scaled scores
‡raw scores

The subject reports “missing” auditory information in school tasks, a condition that may account for the relative weakness in fund of information in spite of high global intelligence. The arithmetic subtest of the WAIS-R is not only a test of mathematical abilities, but due to its format (auditory presentations of mathematical problems to be manipulated without benefit of pencil and paper) it should also be considered a test of auditory manipulation of arithmetic information. Parallel tests of attention span and memory for visual-spatial information and its manipulation (visual-motor tasks) did not reveal similar deficits. In fact, the subject performed in the supranormal range on these tests.

On the Hand Preference Questionnaire (Annett, 1970) the subject showed a profile associated with mixed handedness. She indicated preference for the right hand on eight items, the left hand on two items, and either hand on two items. In view of this finding it is interesting to note, in Table 2, that simple auditory and simple visual reaction times were shorter with the left hand than with the right hand.

EXPERIMENTAL AU迪LOGIC EVALUATION

We administered a series of behavioral tests selected to evaluate monaural, binaural, and soundfield processing of auditory signals. Monaural and binaural tasks were administered via earphones, soundfield tasks via loudspeakers. In the following sections we present, for the sake of continuity, only enough information on methodology to permit an understanding of the figures and tables. Expanded descriptions of methodology are available to the interested reader as appended notes.

Monaural Tasks

Monaural tasks could be classified into two groups: (1) tasks involving the controlled study of rapid temporal analysis, and (2) a task involving the discrimination of differences in duration.

Rapid temporal analysis was studied in two ways; (1) variation in the onset of two pure tones, and (2) variation in the onset of voicing.

To measure variation in pure-tone onset we employed a technique modified from a paradigm originally described by Hirsh (1959) and Hirsh and Sherrick (1961), in which two tones, differing in frequency and by an onset time difference, Δt, are presented simultaneously. In our modification the subject judged whether the two tones were “same” or “different.” Figure 2 shows percent correct “different” judgments for each ear as a function of Δt. The false alarm rate, for trials with no onset difference (Δt = 0), was low in both ears (3 of 225 trials in the left ear; 0 of 225 in the right ear). A pair of tone bursts was presented to the subject at a level of 70 dB SPL. The frequency of one tone burst was 800 Hz, the other 1200 Hz. The 800 Hz burst always had a duration of 500 msec. The onset of the 1200 Hz burst could be delayed, relative to the onset of the 800 Hz burst, by a variable amount. Both bursts, however, ended simultaneously. Thus the only clue to discrimination was the difference in onset times. Performance was measured over a single block of 300 successive pairs of tone bursts. The interpair interval was 2 seconds. The value of Δt was 25 msec in 25 pairs, 50 msec in 25 pairs, 100 msec in 25 pairs, and 0 msec (no onset difference) in the remaining 225 pairs. Thus the a priori probability of a difference was 0.33. We chose this value, rather than the more traditional 0.50, in order to force the subject to adopt a relatively more stringent response criterion. For this task the subject judged whether the two members of the pair were “same” or “different.” Presumably a judgment of “different” was made on the basis of the perception of differing onset times.
Table 2. Norms and Performance Scores of Experimental Subject on Three Measures of Reaction Time

<table>
<thead>
<tr>
<th>Reaction Time Measure</th>
<th>Experimental Subject</th>
<th>Norm* Right</th>
<th>Left</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple auditory</td>
<td>221</td>
<td>220.8</td>
<td>190.1</td>
<td>-13.9</td>
</tr>
<tr>
<td>Simple visual</td>
<td>253</td>
<td>223.0</td>
<td>199.2</td>
<td>-10.7</td>
</tr>
<tr>
<td>Four-choice visual</td>
<td>454</td>
<td>441.9</td>
<td>459.2</td>
<td>3.9</td>
</tr>
</tbody>
</table>


Figure 2 Perception of temporal order. Two tone bursts, differing in pitch, start at different times but end simultaneously. Percent correct discrimination as a function of difference in onset time.

Figure 3 plots percent correct "pa" judgments against voice-onset time in msec. Results are similar for the two ears and show the relatively sharp boundaries characteristic of categoric perception. The voice onset time corresponding to the 50 percent point of the identification function is about 30 msec, a value in close agreement with a range of 25 to 31 msec reported by Jerger et al., (1987) using the same taped tokens on three normal children in the 11 to 12 year age range.

Duration discrimination was measured using a three-tone sequence paradigm suggested by Musiek (1989). Results showed no overall difficulty with duration discrimination. Scores were 97 percent correct on the right ear and 90 percent correct on the left ear. We did note, however, that performance was noticeably poorer for one of the six sequences (SLS) than for any of the other five. For the SLS sequence performance was 80 percent for the right ear, and only 50 percent for the left ear. Figure 4 shows the percentage of errors as a function of the sequence. Included also, in Figure 4, are normative data (mean percent errors and their standard errors), obtained from 10 young adults. The isolated abnormality for the SLS sequence in comparison with results or the other five sequences, in our subject, is readily apparent. The fact that our subject's errors are specific to a

225 trials in the right ear). In general, performance on this task was in good agreement with the 20 msec value reported by Hirsh (1959) for the 75 percent point of the psychometric function relating onset difference to judgment of temporal order. There was no evidence of a significant problem in the appreciation of small differences in onset times of tonal signals.

To measure variation in voice-onset we employed a set of consonant-vowel (CV) stimuli that had been generated on a speech synthesizer at the University of Oregon. The CVs were three formant patterns that differed in the acoustic parameter of voice onset time (VOT). The VOT continuum ranged from 0 to 70 msec in 10 msec increments. Normal listeners perceive the series of stimuli in terms of two discrete categories (ba-pa). Tape recorded stimuli (random series of 30 examples of each VOT variant) were presented monaurally. The intertrial interval was 5 sec. The subject labeled each target that she heard as "ba" or "pa." The examiner recorded the subject's verbal responses. Signals were presented, without background competition, at 60 dB SPL.

The subject heard a sequence of three tone bursts. The duration of each burst was either 250 msec (short, S) or 500 msec (long, L). There were 6 possible permutations of these two durations over a three-burst sequence (i.e., SLS, SSL, SLL, LSS, LSL, and LLS). Each permutation was presented 10 times. The interval between successive tone bursts was 100 msec. The frequency of each tone burst was 1000 Hz. Tones were presented via earphone at 70 dB SPL. A white noise at the same level (0 dB signal-to-noise or S/N ratio) was mixed with the test signal. The subject was seated before a console containing two response buttons. Above each button was a vertical bar. One bar was twice the length of the other. The subject was instructed to listen to a three-burst sequence, then respond by pushing the buttons in the proper order. She was instructed that the button aligned beneath the shorter bar represented the "short" sound, and the button aligned beneath the longer bar represented "long" sound. She was to press the buttons in the same pattern as the sequence of durations heard. The 60 sequences were presented in a predetermined quasi-random order, with the constraint that each of the 6 permutations was presented exactly 10 times.
Binaural Tasks

Binaural tasks could be classified into four groups: (1) a series of tasks involving detection of interaural time and intensity differences, (2) a binaural integration task, (3) a serial recall task, and (4) a series of dichotic listening tasks.

Interaural intensity difference detection was measured using two loudness balance procedures: (1) an alternating binaural loudness balance (ABLB) task and (2) a simultaneous binaural loudness balance (SBLB) task.\(^3\) Interaural temporal difference detection was studied through two paradigms; (1) a binaural temporal balance task (BTB) and (2) an adaptive interaural temporal discrimination task (ITD).\(^4\)

Table 3 summarizes results on the four interaural difference detection tasks, along with the means and standard deviations for a refer-

\(^3\) The stimuli for both procedures were gated clicks (100 \(\mu\)sec on and 100 \(\mu\)sec off), presented in triplets at a rate of one triplet per second. In the ABLB task, click triplets were alternated between the ears. The subject was instructed to adjust the relative intensities of alternating clicks until she perceived them as equally loud in both ears. In the SBLB task, the clicks were presented simultaneously to both ears. The subject was instructed to adjust the relative intensities of clicks until she perceived them as located in the middle of her head. In both tasks, the subject controlled the intensity level of the clicks with a joy stick. When the stick was moved to the right, click intensity was simultaneously increased on the right and decreased on the left. When the stick was moved to the left, intensity changed in the reverse direction. Intensity changes were made in 2-dB increments. Three trials, each with a different starting point, were carried out for both the ABLB and SBLB tasks. The first trial was begun with equal intensities to both ears. In the second and third trials a 20 dB asymmetry was introduced between the ears; first in one direction, then in the opposite direction. The subject's interaural intensity difference, averaged over three trials, was 1.53 dB for each of the loudness balance tasks.

\(^4\) The BTB task was analogous to the procedure described above for the SBLB. The subject was required to adjust the relative arrival times of simultaneous clicks until they were perceived at midline. The stimuli were click triplets presented at an overall intensity of 80 dB peak equivalent SPL. Adjustments in relative arrival times between the two ears were made in 20 \(\mu\)sec increments via joy stick. Again, three trials, with different starting points, were carried out. The temporal difference in arrival times between the two ears when perceived at midline, averaged over three trials, was 33.33 \(\mu\)sec.

The interaural temporal discrimination task was carried out using a four-interval, two-alternative, forced-choice, adaptive-test paradigm. Each trial consisted of clicks presented binaurally during each of four listening intervals, which were labeled sequentially on a computer terminal. In each trial, an interaural difference in arrival time was introduced during either the second or the third listening interval (0.50 a priori probability). The subject's task was to press a button during the interval in which a difference was detected. Differences in arrival times were initiated at 1000 \(\mu\)sec, with the right ear leading. Thereafter, interaural differences were adjusted according to a two-down, one-up rule (Levitt, 1971), wherein the interaural difference was decreased after two successive correct responses and increased after every incorrect response. Testing continued until fourteen response reversals had been obtained. Differences were changed by a factor of 2 through the fourth reversal and by a factor of the square root of 2 for the next 10 reversals. The mean of the last 10 reversals, 58.20 \(\mu\)sec, was taken as the subject's interaural temporal difference limen.
ence group of 12 normal hearing subjects. On the ABLB, the subject’s scores fell within 2 standard deviations of the mean. On the remaining three tasks, the subject’s performance was within 1 standard deviation of the mean. Thus, there was no evidence of difficulty in detecting small time or intensity differences between the two ears.

The Speech with Alternating Masking Index (SWAMI; Jerger et al, 1960) was used to assess the subject’s ability to integrate fragmentary speech information from the two ears. Our subject achieved a maximum of 88 percent correct at both 80 and 100 dB SPL, falling within the range of expected performance for normal hearing listeners (Jerger et al, 1960).

The materials and procedures used in the serial recall task have been detailed previously (Jerger and Watkins, 1988). Figure 5 compares the average percent correct score, across all serial positions, for the visual versus auditory conditions without a suffix, and for the three auditory conditions with and without suffixes. Comparison of the visual versus auditory conditions in the left-hand panel shows better recall for the auditory presentation mode than for the visual mode, a normal modality effect. The auditory advantage was due to an increase in performance for the last one or two items of the auditory list—again, a normal finding, the auditory recency effect. Figure 6 illustrates the magnitude of the recency effect by detailing the serial-position curves for the two presentation modalities.

Results in the right hand panel of Figure 5 show that recall was reduced, as expected, when an irrelevant speech suffix was appended to the auditory list. As with normal subjects, the “suffix effect” did not occur with a noise suffix. Thus the normal distinction between speech and nonspeech suffixes in memory was observed.

In short, serial recall for lists of digits revealed what are widely regarded as cardinal characteristics of normal short-term memory; namely the modality effect, the auditory recency effect, and the speech suffix effect. As shown in Table 1, performance on the digit-span subtest of the WAIS was also within normal limits.

Dichotic listening was explored using three measures: (1) the Staggered Spondee Word (SSW) test (Katz, 1962), (2) the Competing Environmental Sounds (CES) tests (Katz, 1985),

<table>
<thead>
<tr>
<th>Measure</th>
<th>Experimental Subject</th>
<th>Reference Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternate binaural loudness balance</td>
<td>1.33 dB</td>
<td>3.22 dB (1.75)</td>
</tr>
<tr>
<td>Simultaneous binaural loudness balance</td>
<td>1.33 dB</td>
<td>1.66 dB (1.89)</td>
</tr>
<tr>
<td>Binaural temporal balance</td>
<td>33.33 μsec</td>
<td>45.93 μsec (14.02)</td>
</tr>
<tr>
<td>Interaural temporal discrimination</td>
<td>58.20 μsec</td>
<td>56.37 μsec (25.77)</td>
</tr>
</tbody>
</table>

Also shown are means and standard deviations for a reference group of normal hearing subjects (N = 12).

1 The test material consisted of a dual-channel tape-recording to monosyllabic word lists (PAL-PBs) on which were superimposed 500 msec noise bursts. The noise bursts, recorded at a level 20 dB more intense than the words, alternated between the two ears at a rate of one burst every 0.5 sec. When this tape is played through either earphone singly the words are virtually unintelligible; the periodic noise bursts effectively mask all or part of most of the words. When listening through both earphones, however, and provided that the two earphones are phase matched, the listener experiences an illusion in which the bursts of noise are localized to the ears, but the words are localized to the center of the head. The word fragments from each ear are “fused” into a single unitary image. As a result the words are easily understood and the performance score is in the 90 to 100 percent range. For the present subject a performance-intensity function was obtained by presenting 25 words at each of three intensity levels: 60, 80, and 100 dB SPL. The subject’s task was to repeat each of the words. Performance was scored as percent correct at each of three intensity levels.

2 In brief, the task required the subject to reproduce a list of 7 digits presented in one of two modes; auditory or visual. The lists were comprised of the digits 1 through 6 presented via microcomputer at a rate of one item per second. For the auditory mode, items were presented binaurally at 75 dB SPL. For the visual mode, items were flashed in numerical form on the computer screen. For the auditory mode, the subject was tested under three conditions: no suffix, speech suffix (the digit 9), and noise suffix (burst of white noise). For the visual mode, the subject was tested only under the no-suffix condition. Twenty practice items representing the conditions were administered. Then 10 test trials were gathered in each condition. For all trials, a light on a response panel signaled the subject when to begin recall. The subject’s task was to reproduce the list. The subject responded by pushing buttons, labeled 1 through 6 on a response box, in the correct order.
Figure 5  Summary of results of serial-recall paradigm. Average percent correct scores for modality effect (visual versus auditory) and suffix effect (no suffix versus noise suffix versus speech suffix).

Figure 6  Serial position curves for auditory and visual modalities.

and the Dichotic Speech Intelligibility (DSI) test (Fifer et al, 1983).7

The SSW and CES were both administered at 60 dB SPL. For the SSW test, only raw scores were computed. The subject scored 100 percent correct for both ears in all noncompeting conditions. In the competing conditions, she scored 92.5 percent and 97.5 percent for the right and left ears, respectively. On the CES test, the subject scored 100 percent in both ears.

We expanded the Dichotic Sentence Identification (DSI) paradigm to include two monotic control conditions and three additional dichotic test conditions. In the first monotic condition (i.e., “single” sentence condition), the 20 sentences were presented sequentially via a single channel. The subject’s task was simply to report the sentence heard. The purpose of this condition was to ensure that the subject was able to perform the task, in each ear separately, when there was no competing sentence in the other ear. For the second monotic condition (i.e., “double-sequential” condition), pairs of sentences were recorded, one immediately following the other, onto a single channel of cassette tape. The subject’s task in this condition was to report both sentences of the pair after the second sentence had been presented. This condition was incorporated to control for memory. If the subject can correctly report both of the sequential sentences presented monaurally, then memory, per se, cannot be invoked as a basis for poor dichotic performance.

The three dichotic conditions added to the battery differed from the conventional DSI paradigm (i.e., “free recall” condition) only in terms of the instructions to the subject. In the

7The Dichotic Sentence Identification Test (DSI) consists of 90 pairs of sentences randomly selected from the 10 seven-word, third-order sentence approximations comprising the Synthetic Sentence Identification (SSI) Test (Jerger et al, 1968). Each member of the sentence pair has been temporally aligned in the onset and offset to within 100 μsec of the other. In the conventional DSI, sentences are presented at the rate of one pair every ten seconds, via dual-channel cassette tape, simultaneously to the two ears. The 10 sentence targets are listed on a response panel situated in front of the subject. Beside each of the sentences is a response button. The subject is instructed to identify each member of the sentence pair by pushing the corresponding response buttons on the panel. Performance is scored as percent correct identification for each ear according to a free recall format, in which subjects can report either ear first and need not designate the ear in which a specific target was heard.
second dichotic condition the subject was instructed to identify the sentences heard in one ear only (i.e., "focused recall"). By comparing performance in the "free-recall" versus "focused-recall" conditions, the effect of divided versus focused attention could be evaluated. The right ear was designated the ear-of-report for the first 20 items; the left ear for the second 20. In the third and fourth dichotic conditions, the subject was again instructed to report one ear only. In both of these conditions, however, the to-be-reported ear was designated by one of two lights, labeled "right" and "left," located on top of the response panel in front of the subject. In the "pre-cued" condition, the to-be-reported ear was signaled immediately prior to sentence delivery. This condition allowed us to evaluate the subject’s ability to shift attention rapidly from one channel to the other. In the "post-cued" condition, the ear-to-be-reported was signaled immediately following sentence delivery. Thus, the subject was required to attend to, and remember, both sentences until the designated ear-to-be-reported was cued. The ear-of-report was randomized between the two ears in both conditions. In all conditions, sentences were presented at 60 dB SPL.

Figure 7 summarizes results for all DSI test conditions. In both of the monotic conditions, the subject scored 100 percent correct identification in both ears. She also scored 100 percent for the right ear in all four dichotic conditions. However, performance was consistently depressed in the left ear across all dichotic conditions. Thus, while scoring 100 percent in both ears in each of the monotic conditions, the subject showed a relatively consistent ear asymmetry, of 30 to 40 percent, over all dichotic conditions, regardless of attention or memory demands. If such cognitive factors were playing a significant role in the ear asymmetry, we might expect, for example, performance on the left ear to improve, in the focused recall and pre-cued conditions. These conditions are more similar to the monotic conditions where one attends to, and reports, only one ear. Such performance shifts did not, however, occur. The relatively constant ear asymmetry, in spite of variation in cognitive demand, suggests an auditory-specific basis for the performance deficit on the left ear.

**Soundfield Tasks**

Soundfield studies could be classified into two groups: (1) localization tasks, and (2) tasks requiring the suppression of background noise.
Localization tasks included both the absolute localization of sound sources in space and the relative localization of a signal in one field with a different signal in the opposite field. Both studies were carried out in reverberant rooms.

For absolute localization\(^8\) the subject was seated facing 12 loudspeakers mounted on the opposite wall at a distance of 2.7 m. The loudspeakers were arranged in the form of a cross, with the center loudspeaker located directly in front of the subject. Three loudspeakers were located at 9.8 degrees, 19.1 degrees, and 26.5 degrees to the right, left, and above the center loudspeaker. Two loudspeakers were located at 9.8 degrees and 19.1 degrees below center. The loudspeakers were labeled ”1” to ”7” from left to right, and ”A” to ”F” from top to bottom.

In the horizontal condition, the subject’s mean absolute error was 1.9 degrees when facing the loudspeakers, 11.2 degrees with the left ear toward the loudspeakers, and 8.5 degrees with the right ear toward the loudspeakers. In the vertical condition, mean absolute errors were 4.4 degrees when facing the loudspeakers, 4.8 degrees with the left ear toward the loudspeakers, and 4.5 degrees with the right ear toward the loudspeakers. These results, along with the means and standard deviations for a reference group of twelve normal hearing subjects on the same tasks, are listed in Table 4. Results show that the subject performed normally in the absolute localization of clicks in either the horizontal or vertical plane.

For relative localization\(^9\) the subject was seated facing a semicircular table containing two loudspeakers, one to the left of the subject’s midline, the other to the right of midline. One of the two loudspeakers was arbitrarily defined as the “reference” or fixed loudspeaker, the other as the variable loudspeaker. Before each trial the reference loudspeaker was set to an azimuth position of 45 degrees. The variable loudspeaker was then positioned at one of nine azimuths in the opposite field. These positions varied in five-degree steps from 25 degrees to 65 degrees. Our subject consistently localized correctly (three

\(^8\) Absolute localization was tested separately in the horizontal and vertical planes. Stimuli for both of the conditions were clicks presented at 84 dB peak equivalent SPL. For each trial, the subject’s task was to identify the origin of the clicks. She responded by calling out the corresponding loudspeaker number, in the case of horizontal localization, and loudspeaker letter, in the case of vertical localization. For both conditions, the subject was oriented in each of three directions: facing loudspeakers, left ear toward the loudspeakers, and right ear toward the loudspeakers. Twenty-five trials were carried out for each of the three directions. For each trial, the difference in degrees between the selected and the activated loudspeaker was calculated. Accuracy of localization was quantified as the mean of the absolute differences between selected and activated loudspeakers.

\(^9\) The reference loudspeaker was positioned in the right field on 50 percent of trials, in the left field on the remaining 50 percent of trials. The subject’s head was a constant 2.8 m from each loudspeaker position. The test stimuli were pairs of tone bursts presented alternately to the two loudspeakers at 60 dB SPL. The frequency of the tone burst from the reference loudspeaker was always 800 Hz, from the variable loudspeaker always 1200 Hz. The interval between the two test tones was 500 msec. The subject’s task was to indicate, after the presentation of each pair of tones, whether the angle of azimuth of the variable loudspeaker agreed with the angle of azimuth of the reference loudspeaker (i.e., was the tone from the variable loudspeaker as far to the right of midline as the tone from the reference loudspeaker was to the left of midline, or vice versa). The subject responded “same” when the variable tone was localized at the same azimuth, in its field, as the perceived azimuth of the reference tone in the opposite field. The subject responded “right” when the variable tone was localized to the right of the target azimuth in the variable field, and “left” when the variable tone was localized to the left of the target azimuth. Each condition was tested three times. Conditions were sequentially randomized in such a way that the same condition never occurred twice in succession.

### Table 4 Performance Scores of Experimental Subject on Measures of Absolute Sound Localization

<table>
<thead>
<tr>
<th>Measure</th>
<th>Experimental Subject’s Mean (SD)</th>
<th>Reference Group Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horizontal localization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facing forward</td>
<td>1.90° (0.74)</td>
<td>0.80° (0.74)</td>
</tr>
<tr>
<td>Left ear forward</td>
<td>11.20° (4.32)</td>
<td>10.93° (4.32)</td>
</tr>
<tr>
<td>Right ear forward</td>
<td>8.50° (2.98)</td>
<td>7.89° (2.98)</td>
</tr>
<tr>
<td><strong>Vertical localization</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Facing forward</td>
<td>4.40° (2.41)</td>
<td>5.85° (2.41)</td>
</tr>
<tr>
<td>Left ear forward</td>
<td>4.80° (1.61)</td>
<td>6.22° (1.61)</td>
</tr>
<tr>
<td>Right ear forward</td>
<td>4.50° (1.84)</td>
<td>6.36° (1.84)</td>
</tr>
</tbody>
</table>

Data are the mean absolute differences (degrees) between the selected and activated speakers. Also shown are mean absolute differences (±1 standard deviation) for reference group of twelve normal hearing subjects on the same tasks.
out of three trials) when the difference between azimuths was 15 degrees. Nor were there significant field asymmetries. A normal control, a 23-year-old woman tested on the same apparatus, did not do as well, requiring a difference of 20 degrees to achieve the same level of performance. Thus we observed no apparent deficit in the relative localization of sounds.

Background suppression was studied in a sound-treated room. Figure 8 shows the experimental arrangement. The subject was seated equidistant between, and 1.6 meters from, two loudspeakers. A third loudspeaker was mounted on a stand and positioned 0.5 meters above, and slightly behind, the subject's head. A pair of signal lights, labeled "right" and "left", were mounted directly in front of the subject at eye level. The subject's ability to suppress auditory background while attending to auditory foreground was studied in three ways: (1) threshold effects; (2) suprathreshold effects; and (3) a cued target task.

Threshold effects were studied by presenting a target signal (auditory foreground) from either the left or right loudspeakers, while simultaneously presenting a competing signal (auditory background) from either the same or the opposite loudspeaker. Thresholds in the ipsilateral competition (IC) and contralateral competition (CC) modes is represented by solid bars, for the right ear, and striped bars for the left ear. The height of each bar represents the effect of moving the competition from the same side to the opposite side of the head, that is, the extent to which threshold is improved by having the target and competition coming from opposite sides of the head rather than from the same side.

Figure 9 shows that, when the target was presented in the right auditory field, this advantage was typically about 20 dB. When the target was presented in the left auditory field,
however, the advantage was consistently smaller, typically about 10 dB. The magnitude of this ear asymmetry did not appear to be related to either type of target or type of competition.

It is noteworthy, moreover, that such asymmetries were not observed for performance in any condition of ipsilateral (IC) competition. In Figure 10 the same data are replotted to compare the difference between the two sides when the competition was ipsilateral versus the difference between the two sides when the competition was contralateral. When target and competition were presented from the same side (IC mode), threshold asymmetries were slight. Ear differences never exceeded 5 dB for any of the various combinations of target and competition. Larger asymmetries appeared only when the target and the competition were presented in opposite fields (CC mode).

In summary, when threshold measures were used to define ability to suppress auditory background, our subject showed an ear asymmetry of about 10 dB. Unwanted background was less successfully suppressed when the background competition was presented in the right auditory field and the target was presented in the left auditory field.

To measure suprathreshold background suppression we presented SSI sentences at various message-to-competition ratios (MCRs). There were three types of competition; white noise, multitalker babble, and single-talker continuous discourse. When the target was presented via the right loudspeaker the competition was presented via the left loudspeaker and vice versa. Figure 11 summarizes the results of these measures. Percent correct sentence identification is plotted against MCR for each of the three types of background competition. When the
competition was white noise, there was no difference between sides. But when the competition was either multitalker babble or single-talker continuous discourse, performance was better when the target was presented from the right side than from the left side. In terms of MCR, the difference was about 10 dB. In other words, in order to achieve equivalent performance, the MCR had to be made more favorable by about 10 dB when the target was presented in the left field. And, again, such asymmetry did not appear in any of the conditions of ipsilateral competition. The fact that white noise, as competition, did not produce the performance asymmetries that were observed for the threshold measures may be related to the fact that the data of Figure 11 represent only the effects of competition on suprathreshold synthetic sentence identification scores. Previous research (Carhart and Tillman, 1970) has demonstrated that, in this paradigm, noise is a less effective source of competition than is actual speech.

For the cued target task we employed the instrumentation already illustrated in Figure 8. This paradigm represents, for the subject, a relatively difficult case of foreground-background differentiation. The subject must attend to continuous discourse lateralized to one side of the head while simultaneously suppressing noncoherent continuous discourse lateralized to the other side of the head. Then, when a signal light cues the opposite side, the subject must redefine foreground as the discourse coming from the new side, and redefine background as the signal previously defined as foreground. Throughout this alternate cueing, the subject must also suppress the additional background represented by the multitalker babble from above.

In spite of the complexity of this task our subject completed it successfully. She complained, however, that it was more difficult when the left side was cued than when the right side was cued. She volunteered that, “When the babble comes on, the sound from the left loudspeaker gets fainter.” Figure 12 plots percent error scores from each side, both without babble and at various target-to-babble ratios. Whenever the babble was present, the left side showed more errors than the right side, and the magnitude of the difference increased as the target-to-babble ratio became less favorable.

**ELECTROPHYSIOLOGIC STUDIES**

We studied hearing function in a nonbehavioral context by means of three different types of electrophysiologic response: (1) acoustic reflexes, (2) auditory evoked potentials, and (3) otoacoustic emissions.

**Acoustic Reflex**

The morphology of the acoustic reflex was examined by means of special laboratory apparatus.
paratus described elsewhere (Stach and Jerger, 1984). Using dual acoustic probes, both ears are measured simultaneously, yielding averaged reflex waveforms (n=8) for the right crossed and uncrossed, and the left crossed and uncrossed reflex waveforms. For the present study we presented 500 msec reflex-eliciting signals at levels ranging from 90 to 110 dB SPL. Test signals were either tone bursts at frequencies of 500, 1000, 2000, or 4000 Hz, or burst of white noise.

In general reflex morphology was normal for all eliciting signals. All amplitude and latency measures were within normal limits. We did observe, however, that reflex amplitude growth functions tended to be smaller for reflexes elicited by sound to the left ear than for sound to the right ear. Figure 13 illustrates such amplitude growth functions for the 2000-Hz eliciting signal, where the ear difference was most prominent. In both the crossed and uncrossed modes, reflex amplitude was slightly greater when signals were presented to the right ear than to the left ear. Similar differences were observed for all other eliciting signals.

Auditory Evoked Potentials

We measured early (ABR), middle (MLR), late (LVR), and long-latency task-related (LLTRR) auditory evoked potentials by means of conventional averaging procedures.12

In general ABR, MLR, LVR, and LLTRR waveforms were well-formed and within normal ranges for absolute latencies, interpeak latencies, and amplitudes. It was the case, however, that both the N2 - P3 amplitude of the MLR, and the N1 - P2 amplitude of the LVR were smaller with left ear stimulation than with right ear stimulation. Figure 14 shows representative waveforms, and their replicates, for ABR, MLR, and LVR auditory evoked potentials. Figure 15 shows LLTRR waveforms for both right ear and left ear stimulation. Included, also, in Figure 15 is an averaged electro-oculographic response (EOG) from electrodes monitoring eye movement. In the case of LLTRR the displayed waveform is the difference between a baseline condition, in which the frequent signal occurred 100 percent of the time, and the experimental condition, in which the frequent signal occurred 80 percent of the time and the rare signal occurred 20 percent of the time. This algorithm effectively cancels out the LVR, which occurs in both conditions. Thus the difference waveform reflects only the response to the rare event. The LLTRR waveform shows the expected positive peak in the vicinity of 300 msec (sometimes referred to as P3 or P300), indicating a normal task-related potential.

Otoacoustic Emissions

Is it possible that our subject’s auditory problem stems from a subtle cochlear defect not revealed by the conventional pure-tone audiogram? Could the left ear deficit revealed by the various speech audiometric procedures derive

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The active electrode at C2 was referred to the ipsilateral earlobe, for ABR, MLR, and LVR, and referred to linked earlobes for the LLTRR. EEG preamplifiers were Grass P 511, with filters set from 300 to 3000 for ABR, 3 to 3000 for MLR, 1 to 100 for LVR and LLTRR. Filter slope was 6 dB/octave. For ABR we averaged 2560 signals, for MLR 1280 signals, for LVR 160 signals, and for LLTRR 128 signals. For ABR the stimulus was a 100-microsecond, alternating-polarity click. For MLR the stimulus was a 1000 Hz tone pip (2:1:2 configuration) with a total duration of 5 msec. For LVR the signal was a 1000 Hz tone burst with a 5 msec rise-decay time and a total duration of 500 msec. For LLTRR we used the “oddball” paradigm. The frequent stimulus was the 1000 Hz tone burst used for LVR; the rare stimulus was a 500 Hz tone burst of equal duration. Rare stimuli were randomly interspersed among frequent stimuli, except that two rare stimuli were not permitted to occur successively. The a priori probability of a rare stimulus was 0.20. Stimulus rate was 24/sec for ABR, 2.1/sec for MLR, and 0.5/sec for LVR and LLTRR. For ABR the epoch was 15 msec, for MLR 100 msec, for LVR 500 msec, and for LLTRR 1200 msec following a 100 msec, prestimulus baseline.
Figure 13  Amplitude growth functions for both crossed and uncrossed suprathreshold acoustic reflex waveforms.

Figure 14  Early, middle, and late averaged auditory evoked potentials.
Figure 15  Long-latency, task-related averaged potentials generated by "oddball" paradigm.

from left-sided hair cell damage which in some way alters normal speech perception without, at the same time, impacting pure-tone sensitivity? In an attempt to answer this question, we studied transiently-evoked and distortion-product otoacoustic emissions. These measurements were carried out in the laboratory of Dr. Brenda Lonsbury-Martin, Baylor College of Medicine, to whom we are indebted for the otoacoustic emission data and their interpretation. The following summary is condensed from Dr. Lonsbury-Martin’s report:

Transiently evoked emissions were examined in both ears. Each ear emitted a healthy emission, with the left ear exhibiting a slightly larger response. A complete test of distortion-product emission growth functions was accomplished for both ears. These emissions, in general, tended to be slightly larger than normal, except for the right ear at one test frequency...The patient’s otoacoustic emissions, in general, indicate the presence of healthy outer hair cell function in both ears.

Figure 16 summarizes all experimental results, both behavioral and electrophysiologic, on the experimental subject.

DISCUSSION

There is little reason to doubt that this subject has an auditory problem. Her complaints of inability to hear her high-school teachers were sufficient for her to seek professional help. She was even ready to consider using a hearing aid. Nor could her complaints be explained as an example of a student who attempts to blame poor academic performance on a pseudo-hearing problem. She was succeeding academically, had just graduated from high school, and had been accepted at the college of her choice. She was seeking help, not to justify
past failure, but to forestall any problems that
might jeopardize her future academic per-
formance.

Could her problems be explained by a cog-
nitive deficit in attention, memory, or speed of
mental processing? Several lines of evidence ar-
gue against an attentional or memory deficit.
First, the relatively robust LLTRR potential in
the “oddball” paradigm (see Fig. 15) shows that
the subject was able to perform satisfactorily
in an auditory-monitoring task requiring sus-
tained attention. Second, the neuropsychologic
examination showed that, on visual-motor tasks
requiring attention and memory, our subject
performed in the supranormal range. Further
evidence arguing against a memory deficit is the
fact that the subject scored normally on the
Wechsler Memory Scale and on the Digit Span
subtest on the Wechsler Adult Intelligence
Scale. Serial recall for lists of digits (see Figs.
5 and 6) also showed normal modality, recency,
and speech suffix effects, hallmarks of normal
short-term auditory memory. Finally, efforts to
manipulate DSI scores by varying cognitive
demands on memory and attention (see Fig. 7)
were not successful. The fact that performance
was 100 percent on both ears in the double
sequential condition shows that the ability to
remember two sentences long enough to report
both sentences was not at issue. In addition, fur-
ther argument against an attentional problem
was the fact that the DSI asymmetry was the
same whether the subject was asked to report
only what was heard from one pre-cued ear, to
report what was heard in both ears, or to report
what was heard in an ear that was cued only
after the paired sentences had been presented.
The constancy of the performance deficit, in the
face of variation in attentional and memory de-
mands, argues against a cognitive deficit in
either attention, or memory as a viable expla-
nation for the asymmetry in DSI performance.

Finally, evidence against a deficit in speed
of mental processing includes the observations
that intelligence, visual-spatial organizational
abilities, and simple and choice reaction times
(see Table 2) were all either in the normal or the
supranormal range.

What, then, is the evidence for an auditory-
specific, as opposed to an extra-auditory deficit?
Perhaps the most persuasive argument lies in
the asymmetry of auditory abnormalities. On
DSI, and on all soundfield tasks involving a tar-
get in one field and speech competition in the
other field, the left ear was consistently poorer
than the right ear. It is difficult to hypothesize
an extra-auditory deficit capable of producing
such an interaural asymmetry.

Is it necessary to invoke a central mecha-

nism to explain the abnormality? Could the basis
for the left ear deficit be a subtle unilateral coch-
lear defect? Two lines of evidence argue against
this hypothesis. First there is no audiometric
evidence, in either the pure-tone audiograms or
the conventional speech audiometric results, of
a left peripheral disorder. Indeed, pure-tone sen-
sitivity and conventional speech audiometric
scores were, if anything, slightly poorer on the
right ear. Second, examination by otoacoustic
emissions, an exceedingly sensitive measure of
inner ear integrity, failed to disclose asymmetry
in hair cell function.

These various lines of evidence seem to con-
verge on a central, specifically auditory, deficit
involving sound input to the left ear. What can
we say about the nature of this central audi-
atory deficit? First, it does not appear to be a
problem in rapid temporal analysis. The subject
performed normally on tests involving the tem-
poral ordering of pure tones and the perception
of voice onset time. In addition the subject per-
formed normally on a variety of measures re-
quiring the processing of small interaural time
and intensity differences. Furthermore, all neu-
ropsychologic tests with a time component were
in the superior range. Second, it does not appear
to be a problem in azimuth localization. The sub-
ject had no difficulty in the absolute localiza-
tion of clicks or in the relative localization of
pure tones from either auditory field.

The test procedures in which the subject did
have difficulty were; (1) DSI, (2) threshold and
suprathreshold measures of speech understand-
ing in the presence of various types of contra-
lateral competition, and (3) the cued target task
in the presence of speech competition. Each of
these results seems to suggest a fundamental
weakness in the processing of targets delivered
to the left ear when an interfering background
sound was directed to the right ear. Whenever
the experimental structure directed a speech tar-
get to one ear, and some form of competition
either to the other ear or to both ears, our sub-
ject did less well when the left ear was target-
ed. The deficit does not appear to be a problem
in the suppression of background competition,
per se, since there was no asymmetry in perform-
ance when the competing message was deli-
verified ipsilaterally (see Fig. 10). Nor does the deficit appear to be a processing disorder for all inputs to the left ear, since there were many experimental conditions, involving relatively difficult listening tasks, in which the left ear performed as well as the right ear (see Fig. 16).

In summary, the present data suggest that this subject has an asymmetric disorder in the processing of binaural, noncoherent signals. When auditory space was structured such that the target was directed to the left ear, and the competition to the right ear, unwanted background was less successfully suppressed than when the physical arrangement was reserved.

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REFERENCES


