Auditory Afferent and Efferent Assessment Post Functional Hemispherectomy: A Case Study

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We had a unique opportunity to investigate the auditory processing abilities of a 10 year-old female after a left functional hemispherectomy. We administered a comprehensive battery of behavioral and electrophysiological tests, assessing both afferent and efferent auditory pathways. Normal peripheral hearing was established. A normal masking level difference threshold and gap detection threshold were obtained. Normal performance on the Frequency Pattern Test and Duration Pattern Test was also established. However, a right ear deficit was evident on all dichotic speech tests administered. Poor performance on speech-in-noise tests and time-compressed speech tests was noted. The auditory brainstem response was within normal limits, the auditory middle latency response revealed an electrode effect over the left temporal lobe, and auditory late event responses were within normal limits. Suppression of transient evoked otoacoustic emissions was present for the right and left ears. Speech intelligibility in background noise improved with the introduction of contralateral noise for the right and left ears. The introduction of contralateral white noise negatively affected the N1/P2 amplitudes for right and left ear stimulations, and the introduction of contralateral noise did not affect the P3 latency for either ear. The results from this case are important as they demonstrate behavioral and electrophysiological test results in relation to a documented lesion.

Introduction

A hemispherectomy is a rare surgical procedure in which one cerebral hemisphere is removed or disabled. The first published report of an anatomical hemispherectomy was reported over 80 years ago (Dandy, 1928). This procedure has been used as a radical surgical treatment for intractable seizures since 1945 (Krynauw, 1950). Improved surgical techniques and procedures have led to modifications of the total anatomical hemispherectomy to a "functional hemispherectomy." During a functional hemispherectomy, only affected anatomical portions of the central and temporal regions are removed, and the two hemispheres are disconnected (Rasmussen, 1973). This procedure has shown improved control of seizures (Vining et al., 1997).

The improved seizure control and psychosocial improvement following successful surgery outweigh the poor prognosis associated with the natural history of the disease processes. Most hemispherectomized patients do not show a decline of cognitive function in comparison to their preoperative performance, as measured by verbal and performance IQ (Brandt, Vining, Stark, Ansel, & Freeman, 1990; Devlin et al., 2003; McFire, 1961; Pulsifer et al, 2004; Tinuper, Andermann, Villemure & Quesney, 1988; Verity et al., 1982; Wyllie et al., 1998). In fact, an improvement of cognitive function has been reported in some children following hemispherectomy (Devlin et al., 2003).

Normal language and fluent speech have been reported after left hemispherectomy in children with congenital damage (Mariotti, Iuvone, Torrioi & Silveri, 1998; Vargha-Khadem & Polkry, 1992). This provides support for the idea that the right hemisphere assumes language dominance (Stark, Bleile, Brandt, Freeman & Vining, 1995). Further evidence for cortical reorganization after hemispherectomy has been provided by fMRI, showing an increase in activity in the intact hemisphere (Paiement et al., 2008).

Central Auditory Processing and Auditory Lesions

Historically, behavioral tests employed in central auditory processing assessment were originally developed for site-of-lesion testing. Because of similar symptoms, these tests were later used to assess auditory processing. Concern with auditory processing disorders dates back to the 1950s when a group of Italian physicians first reported that patients with temporal lobe lesions had complaints of difficulty understanding speech (Bocca, Calaero, & Cassinari, 1954; Bocca, Calaero, Cassinari & Migliavacca, 1955).

A few years later, Kimura (1961) was first to model the dominant contralateral pathway in dichotic listening tasks. Dichotic testing is a non-invasive method for measuring cerebral hemispheric specialization of auditory processing and laterality. In normal listening conditions, auditory information is conducted to the auditory cortex by both ipsilateral and contralateral auditory pathways; however, during controlled dichotic listening, the ipsilateral pathway is suppressed by the dominant contralateral pathway. A language-related auditory signal presented to the right ear travels through the dominant contralateral right auditory pathway directly to the left hemisphere. Conversely, a language-related auditory signal directed to the left ear is conducted to the right cortex and must be transferred to the left hemisphere via the corpus callosum in order for the person to repeat what was heard in the left ear. Thus, a slight right ear advantage for normal, right-handed listeners is present when listening to dichotic tasks (Berlin, Lowe-Bell, Berlin, Cullen & Thompson, 1973; Kimura, 1961; Lowe, Cullen, Berlin, Thompson, & Willett, 1970). When there is damage or a lesion in the auditory temporal lobe, the ear contralateral to the lesion will be affected in dichotic listening tasks, as the contralateral pathway is the dominant pathway (Berlin, Lowe-Bell, Jannetta, & Kline, 1972).

Previous investigations have reported specific ear advantages (relative to the anatomically lesioned area) in dichotic listening for subjects with agenesis of the corpus callosum (Bryden & Zurif, 1970), partial and complete commissurotomy (Zaidel, 1983), congenital hemiplegia (Brizzolara et al., 2002; Issacs, Christie, Vargha-Khadem & Mishkin, 1996; Korkman & von Wendt, 1995), acquired and congenital brain injury (Nass, Sadler & Sidtis, 1992), and hemispherectomy (Damasio, Lima, & Damasio, 1975; Netley, 1972; Zaidel, 1983). The timing of the lesion onset influences the ear advantage. Congenital lesions may reduce the magnitude of laterality, due to the possibility of increased cortical reorganization (Brizzolara et al., 2002; Fernandes & Smith, 2000; Isaacs, Christie, Vargha-Khadem, & Mishkin, 1996; Woods, 1984).

There are limited published cases reporting behavioral and electrophysiological central auditory processing results after hemispherectomy. Boatman, Vining, Freeman, and Carson (2003) report auditory processing abilities from two hemispherectomy patients, one with right hemispherectomy and one with left hemispherectomy. Both patients received hemispherectomies as children, ages 9 to 9-½ years. Post-surgical testing was done one to one and a half years after surgery. Both patients had good auditory recognition in quiet for speech and non-speech stimuli and had abnormal performance for speech-in-noise testing. The authors purported both hemispheres contribute to speech processing in background noise by the involvement of the efferent auditory pathway and attention. Consistent with previous investigations, both patients reported a deficit in the ear contralateral to the removed hemisphere during dichotic testing.

Auditory Evoked Responses Post Hemispherectomy

There are few studies reporting auditory evoked potential responses after hemispherectomy. Saletu, Itil, and Saletu (1971) reported auditory late event responses (ALERs) in a patient with left hemispherectomy. Responses were obtained from both sides, but the amplitudes were slightly lower on the operated side. Kutus, Hillyard & Volpe (1990) reported the P300 response in five patients post commissurotomy. These investigators found larger response amplitudes over the right hemisphere in comparison to the left. Additionally, they reported that the P300 response is not dependent upon the corpus callosum.

Tong, Xu and Fu (2009) successfully recorded P300 waveforms in six hemispherectomized subjects and a control group. Four subjects were left hemispherectomized and two subjects were right hemispherectomized. No statistical differences in P300 amplitude or latency were reported between the hemispherectomized and control groups. The authors indicated, “A unilateral hemisphere can generate P300 when given certain tasks.” Furthermore, these authors argued, “The basic cognitive function of the two groups was not significantly different, and to some extent, reflects the plasticity of the cerebral hemisphere” (Tong et al. 2009, p 1773). It is important to note that these authors recorded the P300s to binaural stimuli. Therefore, latency and amplitude comparisons between monaural and binaural stimulation were not available. Additionally, amplitude and latency measurements were made only at electrode locations Cz and Pz. Thus, information from additional electrode sites over the site of hemispherectomy was not available.

Auditory Efferent System

The auditory efferent system is not completely understood. The rostral system projects from the cortex to the medial geniculate body and other brainstem auditory nuclei. Most efferent research has focused on the olivocochlear bundle (Rasmussen, 1946; Warr & Guinan, 1979). There are two groups of olivocochlear efferents, the lateral olivocochlear bundle (LOC) and medial olivocochlear bundle (MOC). The LOC efferents are made of unmyelinated fibers and synapse primarily ipsilaterally on the auditory nerve afferents beneath the inner hair cells. The MOC is made up of neurons arising from the peri-olivary nuclei around the region of the superior olivary complex (Rasmussen, 1946; Warr & Guinan, 1979). The MOC efferents are myelinated and the majority of these fibers cross at the floor of the 4th ventricle to the contralateral cochlea and synapse directly with outer hair cells (Rasmussen, 1946).

There are limited ways to assess the auditory efferent system. One of the most recent objective applications is the study of the suppression of otoacoustic emissions (OAEs). With the introduction of noise (delivered either binaurally, ipsilaterally, or contralaterally), the amplitude of OAEs will be reduced in most individuals with normal hearing or normal outer hair cell function (Berlin, Hood, Hurley, & Wen, 1994; Hood, Berlin, Hurley, Cecola, & Bell, 1996). The reduction in OAE amplitude has been attributed to the MOC's influence on cochlear output. To our knowledge, there has not been an efferent investigation specifically studying suppression of OAEs for patients who have had a hemispherectomy.

One behavioral measure of the efferent system has been attributed to the MOC's role in speech perception in noise (Muchnik et al., 2004; Sahley, Nodar & Musiek, 1997). Previous investigators have reported an increase in speech intelligibility scores with the addition of contralateral noise (Giraud et al., 1997; Kumar & Vanaja, 2004). Clinically, an improvement of greater than 10% is considered to be within normal limits (Kumar & Vanaja, 2004) and indicates a functional efferent system. Researchers de Boer and Thorton (2008) reported a positive correlation between the role of the MOC and phoneme-in-noise training. Participants with the poorest ability of discrimination on the first day of training, and who showed the most improvement after training, showed an increase in MOC activity.

Another objective measure of the efferent system is the effect of contralateral noise on the ALER. A decrease in the N1/P2 amplitude and an increase in the P300 latency have been reported with the introduction of contralateral noise (Chueden, 1972; Cranford & Martin 1991; Hurley, Bhatt, Davis, & Collins, 2011; Krishnamurti, 2001; Krumm & Cranford, 1994; Salisbury, Desantis, Shenton & McCarley, 2002; Salo et al., 2003). These changes are reported to be mediated by the efferent system (Salo, Lang, Salmivalli, Johansson, & Peltola, 2003).

The present case provided a rare opportunity to study the afferent and efferent auditory pathways for a number of reasons. There are few cases that provide both behavioral and electrophysiological data from patients with documented central auditory lesions. First, the disconnection of the left temporal lobe from the corpus callosum creates a right-ear deficit in dichotic speech tasks. Second, efferent auditory studies are limited for patients with documented cortical lesions. Last, in patients with documents lesions, electrophysiological recordings are an objective temporal window into the function of the central auditory nervous system (CANS) and may provide useful information about the underlying generators.

Case Report

History

CLH is a female born in January, 2000. She was the product of a full-term pregnancy and birth, weighing 7 lbs-8 oz at birth. At five weeks chronological age, it was discovered that, at approximately 27 weeks gestational age, CLH had suffered a left temporal-parietal infarct in-utero. This resulted in the limited use of her right hand and intractable epilepsy. At age 2, she experienced a grand mal seizure followed by respiratory arrest, and she required CPR afterwards. Grand mal seizures reoccurred at ages 4 and 6 years. Respiratory rescue was required after each grand mal seizure. Ongoing seizures continued, even though pharmaceutical management followed. Seizures remained until January 2009, when a functional modified left hemispherectomy was performed. Since that time, CLH has been seizure free.

Pre- and post-surgical psychological assessments showed no change, indicating CLH fell within the average range of intellectual abilities on the following measures: verbal comprehension, perceptual reasoning, and working memory. Processing speed was in the low- average range.

At the present time, CLH is 11 years of age, mainstreamed in the fifth grade, and performing well academically. This success is attributed, in part, to support services including speech-language therapy and private tutoring two times per week, as well as weekly, private occupational and physical therapy.

CLH was referred to this clinic for a (central) auditory processing disorder [(C)APD] assessment to determine if there were any auditory processing recommendations to support a successful academic career. Testing was completed during two sessions; CLH returned on a separate date for efferent assessments. Parental consent and patient assent for participation in the efferent auditory measures was obtained in accordance with this university's institutional review board policies. CLH was compensated for her participation in this case study.

Peripheral Hearing Assessment

An otoscopic examination indicated clear ear canals, bilaterally. Normal (Type A) tympanograms were obtained bilaterally, and normal ipsilateral and contralateral acoustic reflexes were obtained bilaterally. Pure tone thresholds were within normal limits (< 15 dBHL), bilaterally. Transient evoked otoacoustic emissions (TEOAEs) were obtained using the ILO system (Version 6.0). TEOAEs were present (>3 dB) at all frequencies (1.0, 1.4, 2.0, 2.8, and 4.0 kHz), and wave reproducibility was greater than70%, suggesting normal outer hair cell function. All of these tests are consistent with normal peripheral hearing.

Behavioral Tests for (Central) Auditory Processing

SCAN-3:C. The SCAN-3:C (Keith, 2010), a test for auditory processing disorders in Children, was administered at 50 dB HL. The SCAN-3:C consists of five diagnostic subtests. The first two subtests stress the auditory system by degrading and filtering the speech signal. The Filtered Words subtest uses a 750 Hz low-pass filter and involves presentation of monosyllabic words to each ear, and the Auditory Figure-Ground subtest includes monosyllabic words in the presence of multi-talker babble at a +8 signal-to-noise ratio (SNR). The Competing Words and the Competing Sentences subtests are dichotic, whereby two different stimuli (words or sentences) are presented to the right and left ears. In the Competing Words subtest, the listener is asked to repeat both words, with attention directed to the right ear for the first half of the test and attention directed to the left ear for the remainder of the test. In the Competing Sentences subtest, the listener is required to repeat the sentence in a directed ear, while ignoring the sentence in the other ear. The Time Compressed Speech (60% compression ratio) subtest, which removes the temporal cues of speech intelligibility, was also administered. Results for the subtests are presented in Table 1. It is important to note, scoring for the SCAN-3:C is interpreted from the combined right and left ear. In other words, right and left individual scores are added together for the raw score, and the Standard score is derived from the raw score.

CLH performed within normal limits for the Auditory Figure Ground, Filtered Words, and Time Compressed Speech subtests. A right ear deficit was revealed on the Competing Words and Competing Sentences subtests.

The Dichotic Digits Test (Musiek, 1983) was also administered. In this test, two numbers are presented to the right ear at the same time two different numbers are presented to the left ear. The listener must repeat all four numbers. This test assesses the ability of the auditory system to integrate information from the right and left cerebral hemispheres and is scored based on the percentage of digits repeated correctly. CLH scored 40% for the right auditory pathway and 92% for the left auditory pathway. These discrepant scores reflect a right ear deficit.

A Three-Interval Forced Choice Gap Detection Test (Davis & Hurley, 2002) was administered. This test is a variation of the Gaps in Noise (GIN; Musiek et al, 2005) and is used as a temporal resolution screening tool. In this test, three bursts of noise are presented with one of the bursts having a silent interval that varies from 2 to 20 msec in length. The listener must identify which burst in the series has the silent interval by indicating "1, 2, or 3" or "first, middle, last." CLH was able to detect a 3 msec silent interval in both the right and left ears separately, and these results are within normal limits.

Frequency Pattern Test (FPT) and Duration Pattern Test (DPT). The FPT (Musiek & Pinheiro, 1987) and DPT (Pinheiro & Musiek, 1985) require auditory discrimination, temporal ordering, and pattern recognition. Both tests are similar in composition. These tests were included because previous investigators report that patients with hemispheric or interhemispheric dysfunction may have difficulty in the ordering of sound sequences (Bamiou et al., 2006; Musiek, Baran, & Pinheiro, 1990).

Tones in the FPT test are 200 msec in duration with a 10 msec rise-fall time. The inter-toneburst interval is 150 msec, with a 7 sec inter-pattern interval. For the FPT, three low- and high-frequency tones are presented to the listener. Two are the same and one is different. The listener must identify and then verbalize the pattern with a response, such as "low, low, high" or "high, low, low." The frequency of the low tone is 880 Hz, and the frequency of the high tone is 1122 Hz. CLH scored 100% when tones were presented separately to the right and left ears.

In the DPT, the 1000 Hz pure tones are either "short" (250 msec) or "long" (500 msec). Three tones are presented to the listener. Two are the same and one is different. The listener responds by identifying and then verbalizing the pattern, such as "long, long, short" or "short, long, long." The test is scored on the percentage correct for each ear. CLH scored 80%, when tones were presented to the left ear and 92% when tones were presented to the right ear. These scores are within normal limits (Bellis, 2003).

Masking Level Difference (MLD). A MLD was obtained where thresholds were compared between two conditions: (1) 500 Hz tone and noise in phase (S0, N0), and (2) 500 Hz tone was out of phase with the contralateral signal and the noise was in phase with the contralateral noise (SπN0; Hirsh, 1948; Olsen, Noffsinger, & Carhart, 1976; Olsen, Noffsinger, & Kurdziel, 1975). CLH had a normal MLD of 10 dB (Olsen et al, 1976).

Results from the behavioral test battery are summarized in Table 1. This summary table groups the tests according to classifications of monaural low redundancy, dichotic tests, and tests of temporal pattern or temporal processing (Bellis, 2003).

Electrophysiologic Recordings

Electrophysiologic recordings were obtained while the

Table 1. Summary of behavioral (central) auditory processing disorder tests.

Task	Test	Result
Monaural Low Redundancy Tests	Auditory Figure Ground (SCAN-3:C sub-test)	*Normal
	Filtered Words (SCAN-3:C sub-test)	Normal
	Time Compressed Speech (SCAN-3:C sub-test)	Normal
Dichotic Listening Tasks	Competing Words (SCAN-3:C sub-test)	*Normal Right Ear Deficit
	Competing Sentences (SCAN-3:C sub-test)	Abnormal Right Ear Deficit
	Dichotic Digits	Abnormal Right Ear Deficit
Temporal Pattern	Frequency Pattern Test Duration Pattern Test	Right: Normal Left Normal
	Gap Detection Threshold	Right: Normal Left: Normal
	Masking Level Difference	Normal

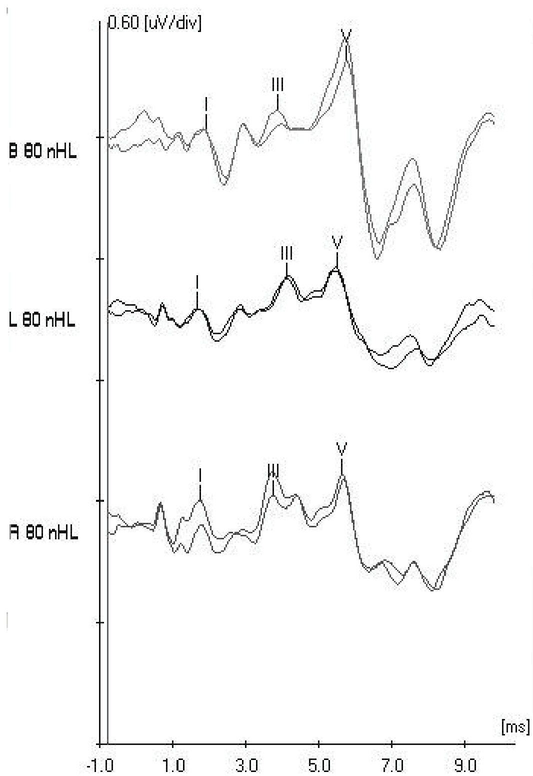
*1 Standard deviation below the mean.

subject rested comfortably in a reclined position and watched an animated movie with the sound muted. These recordings were obtained to assess the integrity of the CANS from the brainstem through the auditory cortex. Stimulus parameters for the auditory brainstem response (ABR), speech ABR, auditory middle latency response (AMLR), and auditory late event response (ALER) are presented in Table 2. All recordings were made with three surface electrodes attached to the skin at the vertex (non-inverting) and each ipsilateral mastoid (inverting). Electrode impedance was below 5000 ohms for all recordings, and stimuli were delivered to the ear by ER3A insert earphones.

Table 2. Parameters for auditory brainstem response (ABR), speech auditory brainstem response (speech ABR), auditory middle latency response (AMLR), and auditory late event response (ALER).

Parameters	ABR	Speech ABR	MLR	ALER
Time Window	12 msec	100 msec	100 msec	750 msec
Number of Sweeps	2000	3000	1000	
Stimulus	100 μsec Condensation Click	40 msec “da”	Click	Standard: 500 Hz Rare: 2000 Hz
Presentation Rate	27.7	11.1	6.7	1.1
Filter Settings	100-3000	100-2000	5-100	1-30
Stimulus Sequence	2 runs of 2000 clicks	2 runs of 3000	2 runs of 2000 clicks	2 runs 1000 simuli 80% frequent 20% rare
Stimulus level	80 dBnHL	80 dBSPL	70 dBnHL	
Artifact Rejection	Yes	Yes	Yes	Yes
Number of channels	1	1	2 Cz: A1 Cz: A2 C3:A1 C3-A2 C4: A1 C4: A2	2

Figure 1. A normal auditory brainstem response was obtained for binaural (B), right (R), and left (L) stimulations.



Auditory Brainstem Response (ABR). The normal ABR is shown in Figure 1, and the latency and amplitude values of Wave I, III, and V are reported in Table 3. This ABR is within normal clinical values (Hall, 2007).

Speech Auditory Brainstem Response. Two repeatable recordings of the speech ABR were obtained and then added together for a grand average speech ABR response. The grand average was compared to a normative recording for an algorithmic, numeric score that is interpreted by the BioMARK proprietary software as “normal, borderline, or abnormal.” The left and right monaural summed waveforms are shown in Figure 2. Wave V latencies and the BioMARK algorithmic numeric scores are

Table 3. Auditory brainstem response latency and Wave V amplitude measures.

	Wave I (msec)	Wave III (msec)	Wave V (msec)	Wave V amplitude in μV
Binaural	1.91	3.86	5.70	.97
Right	1.74	3.74	5.70	.36
Left	1.66	4.11	5.49	.45

Figure 2. Normal BioMARK recordings for the right and left ears.

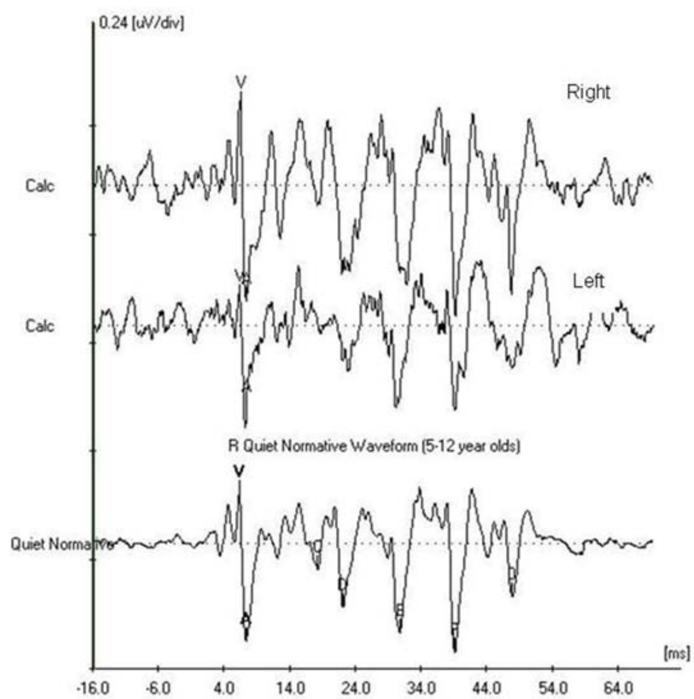


Table 4. Latency information for Wave V and Wave A, and the BioMARK algorithm score for the speech auditory brainstem response.

	Wave V (msec)	Wave A (msec)	Algorithm Score
Right	6.53	7.45	1
Left	6.45	7.45	4

displayed in Table 4. The algorithm scores are within normal limits and reflect normal encoding of speech stimuli.

Auditory Middle Latency Response (AMLR). The amplitude of the Na-Pa wave complex for the AMLR was obtained by summing the two individual runs. Investigators have previously reported amplitude measures may be more sensitive than latency measurements (Chermak & Musiek, 1997; Kraus, Ozdamar, Hier, & Stein, 1982; Scherg & Von Cramon, 1986). Latency and amplitude values for each electrode site and stimulation are reported in Table 5. The amplitude for electrode C3 is greater than 50% less in comparison to other electrodes. Amplitude measures that are less than 50% in comparison to other electrode sites are diagnostically significant (Chermak & Musiek, 1997; Musiek, Charlette, Kelly, Lee, & Musiek, 1999. (This is shown in Figure 3, and amplitude and latency values are given in Table 5.)

Auditory Late Event Response (ALER). The ALER recordings were obtained using an "oddball" paradigm (Squires & Hecox, 1983). The software selection for this oddball paradigm ratio was 80/20, indicating the frequent stimulus would be presented 80% of the time, and the rare tone would be presented 20% of the time. Although the standard recording procedure requires the subject to attend or count the infrequent or rare stimuli, this recording was obtained passively. No instructions were given to CLH, and she sat and watched a muted, animated movie. Latency and amplitude values for monaural and binaural stimulations are shown in Table 6 and in Figure 4. The P3 is interpreted as within normal limits (Hall, 2007). On a clinical note, P3 is used when an oddball paradigm is passively recorded; P300 is used when the listener is instructed to attend to novel stimuli.

Efferent Assessment

Contralateral suppression of TEOAEs. TEOAEs were obtained in response to an 80 dB peak equivalent SPL "non-linear" click in the right and left ears. The ILO "non-linear" click consists of three, in-phase, 80 µs square wave clicks followed by a fourth out-of-phase click with a 10 dB higher intensity. Three TEOAEs in quiet and three TEOAEs obtained in the presence of 45 dBHL white noise were delivered to the contralateral ear via

Figure 3. The auditory middle latency response (AMLR) recording.

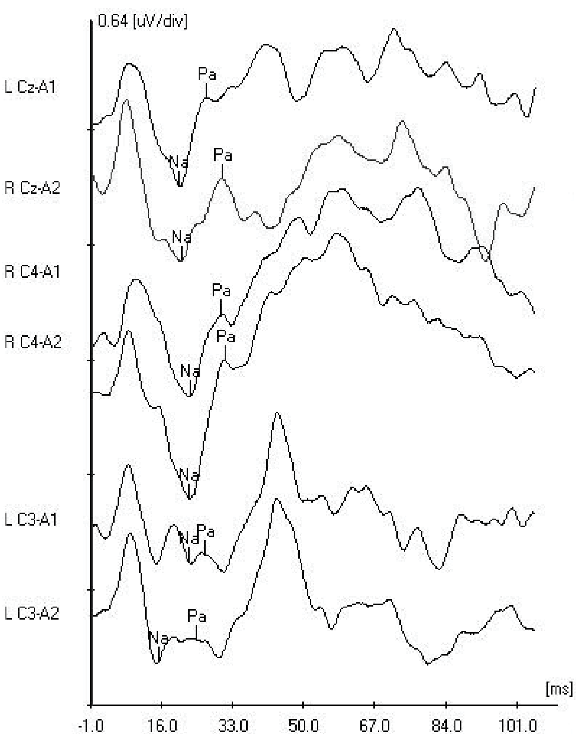


Figure 4. Auditory late event response and P300 recordings.

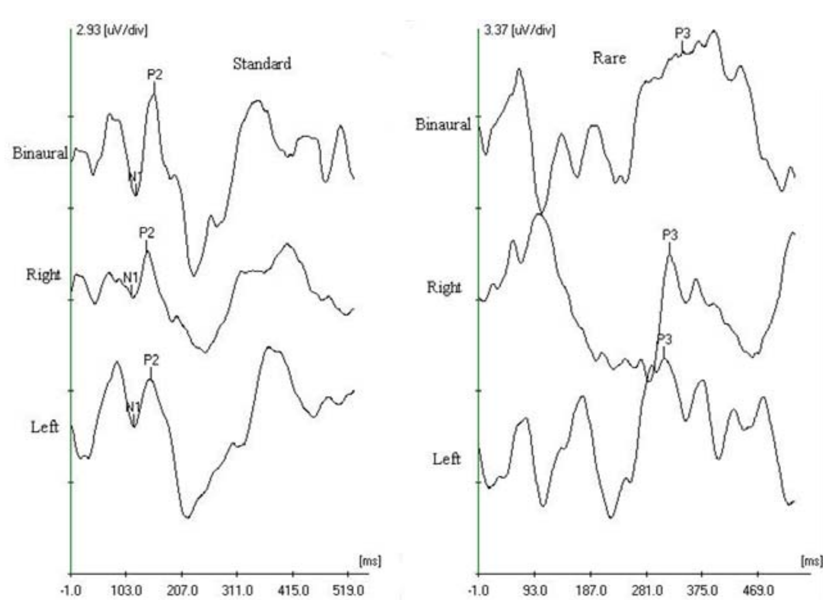


Table 5. Latency and amplitude information for the auditory middle latency response. An electrode effect was evident for recording over the left temporal lobe (electrode site C3).

Electrode	Stimulus Ear	Na latency (msec)	Pa latency (msec)	Na-Pa amplitude in µV
Cz	Left	20.02	26.68	.49
Cz	Right	20.85	30.64	.45
C4	Left	22.94	30.22	.44
C4	Right	22.52	31.06	.76
C3	Left	22.52	26.47	.08
C3	Right	15.23	24.39	.12

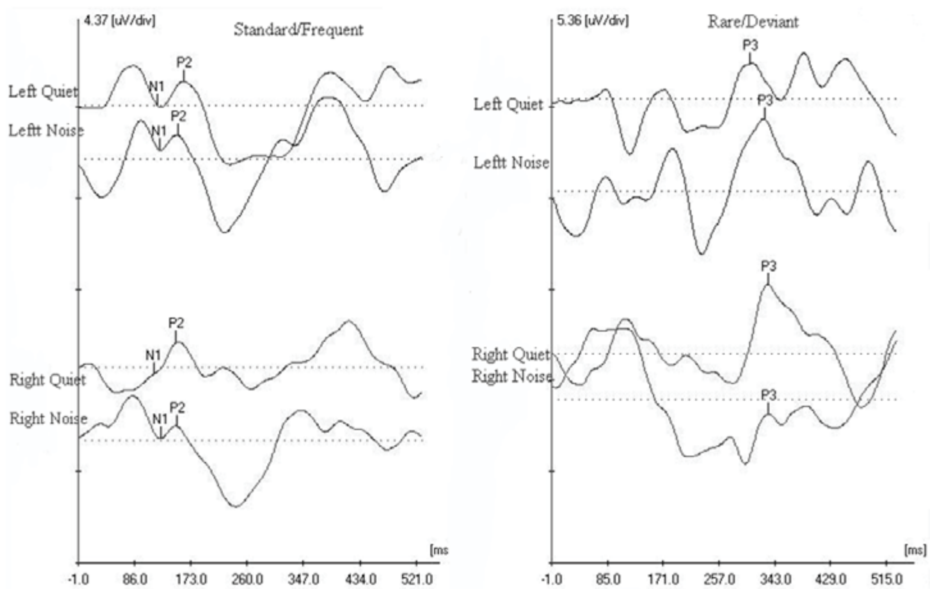
Table 6. Latency and amplitude information for the P300 recording.

Ear	N1 latency (msec)	P2 latency (msec)	N1/P2 amplitude in µV	P300 latency (msec)	P3 amplitude in µV
Binaural	121	155.35	3.25	304.22	1.83
Right	123.71	144.94	1.44	319.60	1.91
Left	116	144.94	1.41	311.50	2.97

Table 7. Contralateral suppression of transient evoked otoacoustic emissions.

	Mean Amplitude in Quiet in dB	Mean Amplitude in Noise in db	Overall Suppression in dB	1kHz	1.4 kHz	2 kHz	2.8 kHz	4 kHz
Right	21.93	21.40	.53	1.23	.53	.23	.77	.27
Left	18.87	18	.17	2.10	1.47	-1.03	-.10	.17

Figure 5. The auditory late event response in quiet and in noise.



insert earphone. A slightly greater TEOAE amplitude was obtained for the right ear in quiet conditions as compared to the left ear in quiet. The right ear also had slightly more suppression of TEOAE amplitude (noise was delivered to the left ear). Table 7 provides TEOAE values for each condition. These findings are consistent with previous investigations, showing slightly greater suppression for the right ear with contralateral noise (Hood et al., 1996).

Speech intelligibility in ipsilateral and contralateral noise. Behavioral assessment of the efferent system was obtained by measuring the performance of speech intelligibility with ipsilateral four-talker babble and with the introduction of contralateral white noise. Speech stimuli consisted of 50 NU-6 monosyllabic words with speech babble in the ipsilateral ear at +10 SNR. For the first half of the word list, the speech and noise were presented to the ipsilateral test ear. During the second half of the word list, the speech and noise were still presented to the ipsilateral test ear, but white noise at 40 dB HL was also delivered via insert earphone to the contralateral ear. Therefore, each condition yielded an intra-aural comparison.The right ear showed an improvement of 16% (28% with ipsilateral noise; 44% with ipsilateral and contralateral noise), and the left ear showed a similar improvement of 12% when contralateral white noise was introduced (72% with ipsilateral noise; 84% with ipsilateral and contralateral noise). As noted earlier, an improvement greater than 10% is considered within normal limits clinically (Kumar and Vanaja, 2002) and reflects a normal functioning efferent system.

Auditory cortical potentials with contralateral noise. Auditory evoked late potential recordings obtained with the oddball paradigm described in an earlier section were recorded in quiet and in the presence of contralateral 50 dB HL white noise. A decrease in the N1/P2 amplitude was obtained when contralateral white noise was delivered to both ears. Additionally, an increase in P3 latency was obtained when contralateral noise was delivered to the right ear, but not when the noise was delivered to the left ear (signal in right ear). Amplitude and latency values for ALER and P3 responses are listed in Table 8 and shown in Figure 5.

Discussion

The results of the behavioral and electrophysiological test results are consistent with anatomical function. The functional hemispherectomy involved disconnection of the left auditory temporal lobe from the corpus callosum. Input from the ipsilateral and contralateral pathways remain present; however, we cannot be sure of the functional capabilities of the left auditory cortex. Normal peripheral hearing was established by pure tone thresholds, tympanometry, acoustic reflexes, and TEOAEs.

Behavioral Assessment

Behavioral central auditory processing disorder tests were consistent with previous site of lesion investigations. As expected, this patient displayed a right ear deficit (the ear contralateral to the

Table 8. The auditory late event response and P300 recordings in quiet and with contralateral noise.

Ear	N1 latency (msec)	P2 latency (msec)	N1/P2 amplitude (µV)	Percentage of Amplitude Reduction	P3 latency (msec)
Right Quiet	114.75	144.35	1.56	59%	333.37
Right Noise	126.20	151.19	.64		333.07
Left Quiet	129.33	163.68	1.22	38%	305.26
Left Noise	122.24	151.19	.76		321.91

lesion) on all dichotic speech tests administered, the Competing Words and Competing Sentences of the SCAN-3:C, and the Dichotic Digits Test. Speech introduced to the right ear must be processed via the right ipsilateral pathway in the right hemisphere, and speech introduced to the left ear travels directly to the right hemisphere for processing. The contralateral auditory pathway is dominant. In dichotic listening, the ear contralateral to the lesion will be suppressed; thus, CLH's right ear deficit is evidence of the functional left hemisphere.

Consistent with previous investigations, CLH performed within normal limits on the FPT and DPT. Dennis & Hopyan (2001) reported normal rhythm perception in children with either right or left temporal lobectomy. Melody deficits related to pitch perception were reported in subjects who had right temporal lobectomy. Suprasegmental aspects of speech are processed in the right hemisphere. CLH's ability to correctly linguistically label the pattern is evidence of the migration of language to the right hemisphere.

A normal MLD was obtained. The MLD is mediated by the lower brainstem and is often abnormal in patients with brainstem lesions (Lynn & Gilroy, 1977; Olsen et al., 1976); whereas, cortical lesions have shown no effect on the MLD (Cullen & Thompson; 1974).

CLH performed within normal limits, but one standard deviation below the mean on the Auditory Figure Ground subtest of the SCAN-3:C. This score is based upon combined individual right and left scores. Previously, poor speech-in-noise performance was reported in two patients with hemispherectomy (Boatman et al, 2003). The authors attributed this deficit to a possible deficit in the efferent system.

Electrophysiological Assessment

A normal ABR response was obtained in this case. This obligatory response is mediated by structures from the distal portion of the VIII nerve through the superior olivary complex. These normal responses are not surprising, as the generators from this response are in the brainstem and midbrain and not anatomically affected by the functional hemispherectomy.

An electrode effect for the left temporal lobe C3 was indicated by the AMLR. The underlying auditory generators of the MLR include the thalamocortical pathway, the reticular formation, and the inferior colliculus (Kraus et al., 1982). Previous investigations of the AMLR in patients with temporal lobe lesions have been conflicting. A normal AMLR was reported in one patient with auditory agnosia and temporal lobe lesions (Parving, Solomon, Elberling, Larsen, & Lassen, 1980). Kraus et al. (1982) reported diminished Pa amplitude over the lesioned side in 24 patients with temporal lobe lesions. The latter study is consistent with our results.

The ALER in this case was within normal latency values. Researchers agree that the exact neural generators for the ALER are not known (Clayworth & Woods, 1987; Wood & Wolpaw, 1982). Most agree the auditory cortex, auditory association areas and other structures, such as the limbic system, hippocampus, amygdale, and thalamus, are all involved in the generation and regulation of the ALER and P300. Additional information from numerous electrode sites would be of interest for hemispherectomy cases.

Efferent Assessment

One of the functions of the auditory efferent system has been linked to enhancement of speech understanding in noise. Boatman et al. (2003) attributed the difficulty of speech understanding in noise in two patients with hemispherectomies to a dysfunctional efferent system. The speech-in-noise deficit may be attributed to the right hemisphere's responsibility for processing all spectral and temporal information and reflect more demands on the remaining hemisphere, rather than two specialized hemispheres. Again, the remaining functional capabilities of the left hemisphere are not completely known.

Contralateral suppression of TEOAEs was evident for both the right and left ears, suggesting a normal finding. The reduction of amplitude is likely mediated by the olivocochlear bundle crossing to the contralateral cochlea. Consistent with previous investigations, this patient displayed slightly more TEOAE suppression for the right ear (contralateral noise delivered to the left ear). Contralateral suppression of TEOAEs is mediated by the MOC (Berlin et al., 1994; Collet et al., 1990; Hood et al, 1996). This is, again, consistent with previous investigations, showing more suppression in the right ear in normal hearing adults (Khalfa & Collet, 1996).

An improvement in speech intelligibility in noise with the introduction of contralateral noise was documented for the right and left ears. This is in agreement with previous investigations and supports efficient function of the MOC efferent system (Giraud et al., 1997; Kumar & Vanaja, 2004).

A reduction of amplitude in the N1/P2 response was observed when contralateral noise was presented to the right and left ears. Again, this change was noted in both ears and represents normal function of the efferent system (Salo et al., 2003). The lack of increase in P3 latency for the right ear with the introduction of contralateral noise may be related to the stimulus recording. (CLH was given no instructions to attend to the rare or deviant stimuli.)

Previous investigators (Cranford & Martin, 1991; Krumm & Cranford, 1994) have shown no statistically significant differences between the right and left N1/P2 amplitude reduction when contralalteral noise was introduced. Also, Hurley et al. (2011)

reported no significant differences in the amount of reduction in the N1/P2 amplitude between a group of children with (C)APD and a control group when noise was introduced contralaterally.

Researchers have also reported an increase in P300 latencies with the introduction of contralateral noise (Krishnamurti, 2001; Polich, Howard, & Starr 1985; Salisbury et al., 2002). The addition of contralateral noise did not significantly affect the P300 amplitude. Hurley et al. (2011) reported a sighificant increase in P3 latency when contralateral noise was introduced for the control group, but no significant latency change in the P3 latency with the addition of noise for the experimental group (i.e., children diagnosed with (C)APD). The different effect of noise on the P3 may be attributed to obtaining the recording passively with no instructions given. It is also important to note the variability of these responses. Additional research is needed.

It is important to consider that this patient was referred to this clinic for evaluation and recommendations because of her hearing in background noise. Classroom frequency modulation (FM) system use and dichotic listening training, such as Dichotic Intensity Interaural Difference training (Musiek, Chermak, & Weihing, 2007), were recommended. CLH is currently performing above average in a private school. She is socially adjusted with many friends and social activities.

Summary

In summary, this clinical case report is important to further our understanding of a documented CANS lesion on behavioral and electrophysiological tests of auditory processing. This left lesion was supported behaviorally by dichotic speech tests and electrophysiologically by the electrode effect over the left temporal lobe. This case report is also the first to report normal efferent function for a post hemispherectomy patient.

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