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Auditory Processing following Sequential Bilateral Cochlear Implantation: A Pediatric Case Study Using Event-Related Potentials

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Abstract

Background: Past studies using event-related potentials (ERPs) elicited to single syllable stimuli in unilateral and bilateral cochlear implant users have suggested reorganization of the auditory cortex within the first 6–8 mo postimplantation (Sharma et al, 2002a, 2002b, 2006; Bauer et al, 2006). Better behavioral performance with bilateral implants is expected when bilateral cochlear implantation is performed simultaneously or when a second implant is provided after a short interval of auditory deprivation at a younger age (Murphy and O'Donoghue, 2007; Wolfe et al, 2007; Steffens et al, 2008).

Purpose: The purpose of this case study was to examine changes in various levels of auditory processing using single syllable and word-level stimuli in a child who received bilateral cochlear implants sequentially.

Research Design: Brain responses were recorded at pre-activation and 2, 4, and 6 mo postactivation of a second cochlear implant using passive paradigms involving two types of auditory perception (speech and word level). Auditory stimuli were presented at 75 dB SPL(A) through a speaker above the participant's head with the cochlear implant(s) at typical user settings. Cortical responses were recorded from 128 electrodes.

Study Sample: The participant was a 6-yr-old female with the diagnosis of bilateral profound sensorineural hearing loss. She received her first cochlear implant in her right ear (2 yr, 4 mo of age), underwent revision surgery (3 yr, 6 mo of age), and later received a bilateral cochlear implant (6 yr, 8 mo of age).

Data Collection and Analysis: For the purposes of the case study, the waveforms were visually examined for morphology and amplitude or latency differences between conditions. The ERPs of the cochlear implant user were compared to those from a group of five children with normal hearing.

Conclusions: The results suggest that sequential bilateral cochlear implantation contributes to improved auditory processing beyond the benefits of the single implant even in users with an extended period of deafness in the later-implanted ear.

Key Words: Bilateral, cochlear implant, event-related potentials, speech, syllable

Abbreviations: ERP = event-related potential; HINT-C = Hearing in Noise Test-Children; ISI = inter-stimulus interval; PBK = open-set word-recognition task; PTA = pure tone average

Listening with two ears offers specific advantages for auditory processing. The head shadow effect improves the audibility of signals in cases in which signal-to-noise ratio (SNR) varies at the two ears. Binaural redundancy can help to maximize audibility in cases where similar information is presented to both ears. Binaural squelch diminishes the perceived interference of noise. For these reasons, it is standard of care to provide two hearing aids to children and adults with aidable bilateral hearing loss. Similarly, after more

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than 20 years of only recommending implantation in one ear, cochlear implant centers have started to offer bilateral cochlear implantation.

Users of bilateral amplification report greater ease of listening (Noble and Gatehouse, 2006) and improved quality of life (Orabi et al, 2006). Both adults and children experience improvements in speech perception, localization, and speech intelligibility in noise due to the availability of binaural cues typically utilized by persons with normal hearing (Grantham et al, 2007; Ricketts et al, 2006; Ching et al, 2007; Galvin et al, 2007; Gordon et al, 2007; Murphy and O'Donoghue, 2007; Steffens et al, 2008; Wolfe et al, 2007). In children aged 3 to 13 yr, good open-set speech perception in quiet and noise using the second cochlear implant alone has been reported within 6 mo postimplantation, and bilateral benefits for spondee perception in noise has been shown to increase between 3 and 9 mo postimplantation (Peters et al, 2007). Localization abilities may take up to 1 yr of bilateral experience to develop (Litovsky et al, 2006).

While the potential benefits of bilateral cochlear implants are easily identified, questions regarding the associated auditory development remain. The same factors that affect the outcomes of unilateral cochlear implantation (e.g., age at implantation, duration of deafness, preschool and educational setting, etc.; Waltzman, 2000) are also considered in the context of bilateral implants. The age at which children are implanted with a second bilateral cochlear implant has an effect on listening in quiet and in noise. Improvements in auditory abilities are more salient in cases where bilateral cochlear implantation is performed simultaneously or when a second implant is provided after a short interval of auditory deprivation at a younger age (Murphy and O'Donoghue, 2007; Wolfe et al, 2007). Specifically, children who receive a second cochlear implant between 3 and 5 yr of age demonstrate better speech perception in quiet and have better scores on the *Multisyllabic Lexical Neighborhood Test* (MLNT) and the *Lexical Neighborhood Test* (LNT) at 12 mo postimplantation compared to children who receive a second implant between 8 and 13 yr of age (Peters et al, 2007). Steffens et al (2008) noted that bilateral performance is correlated with age at second implantation, interimplant interval, and also the length of experience with the second cochlear implant. Similarly, Wolfe et al (2007) reported that in sequentially implanted children (aged 1.5–9.5 yr), increased duration of deafness in the second ear typically results in decreased speech perception in quiet in a monaurally aided paradigm using the second implant. After at least 1 yr of bilateral cochlear implant use, however, speech in noise scores improve regardless of age at second implantation (Wolfe et al, 2007).

A number of studies have examined central auditory processes associated with cochlear implantation. Auditory processing takes place in fractions of a second, and unlike behavioral assessments and most imaging techniques, brain measures such as event-related potentials (ERPs) offer an opportunity to examine sound processing with comparable temporal resolution. ERPs are a portion of the ongoing electroencephalogram (EEG) that is time-locked to the precise onset of a stimulus presentation (e.g., click, syllable) and reflect the change in the EEG associated with the processing of that stimulus (Fabiani et al, 2000). ERPs have advantages over behavioral assessments because they can reflect subtle psychophysiological reactions to presented information even in the absence of overt responses by the participant. ERPs are typically described in terms of positive and negative peaks. Many of the peak characteristics (e.g., latency, topographic distribution of maximal activity on the scalp) have been linked to specific stages of information processing and brain areas (Key et al, 2005). Recently, ERPs have become a valuable tool in investigating brain mechanisms of auditory processing in cochlear implant users.

Studies using ERPs in unilateral cochlear implant users have shown that the auditory cortex undergoes rapid reorganization within 6-8 months post-implantation as indicated by changes in several ERP components (Sharma et al, 2002a, 2002b). Some evidence of stimulus processing and discrimination has been seen within days after initial processor fitting (Jordan et al, 1997). Increased duration of cochlear implant use has been associated with faster sound processing as reflected by latency decrease (Kelly et al, 2005). In a series of studies, Sharma et al (2002a, 2002b) documented that children implanted unilaterally by 3.5 yr have P1 latencies similar to age-matched normal hearing peers within 6–8 mo of implantation. This growth is a reflection of faster than typical maturational rate. For children implanted after 7 yr of age, the P1 latency continues to decrease over time but remains outside of the typical range even after 2 yr of cochlear implant use (Sharma et al, 2002a).

Other ERP peaks associated with auditory processing reveal potentially atypical cortical maturation in cochlear implant users. The auditory N1 is thought to reflect activity of the upper layers of the auditory cortex. Unlike the deeper structures, maturation of these upper layers is experience dependent and does not occur if adequate auditory stimulation is not available early in life (Sharma et al, 2002b). Thus, it is not uncommon to see a missing or immature N1 peak in cochlear implant users with prolonged periods of deafness during childhood (Ponton and Eggermont, 2001). N1 latencies in adults with unilateral cochlear implants are delayed for auditory stimuli (e.g., tones, vowels, syllables) and show reduced amplitudes for speech (Makhdoum et al, 1998; Groenen et al, 2001). A missing N1 response may also suggest greater difficulties with processing speech in noise, as maturation of the upper cortical layers coincides with improvements in perception of degraded speech (Eggermont and Ponton, 2003). Increased amplitude of the N1-P2 complex and decreased latency of P2 have been associated with better scores on behavioral measures of speech perception (spondee identification; Makhdoum et al, 1998).

ERP studies involving bilateral cochlear implant users are not as numerous; however, a limited number of studies exist in the current literature. For example, Bauer et al (2006) examined the time course of P1 latency maturation in infants with sequential and simultaneous bilateral cochlear implants. This work suggests that infants who receive bilateral cochlear implants simultaneously show P1 latencies similar to those of age-matched hearing peers by 1 mo postactivation. Further, infants who receive two cochlear implants sequentially by 12–24 mo of age show P1 development similar to that of unilateral cochlear implant users. That is, after receiving a single implant, latencies can fall within normal limits by 3–6 mo post-implantation. After receipt of a second cochlear implant, P1 latencies can fall within normal limits 1 mo following implantation. A similarly rapid normalization of P1 was reported in a child who received sequential implants prior to the age of 3.5 yr, but not in a child who received the second implant after 7 yr of age whose ERPs remained similar to those observed in late-implanted unilateral implant users (Sharma et al, 2005).

Existing ERP studies provide important information regarding changes in brain mechanisms associated with hearing and improve our understanding of reasons for differential outcomes in early- and late-implanted children. These studies, however, primarily focused on a limited number and type of auditory stimuli (e.g., single syllables or brief clicks) and require minimal auditory processing beyond basic sound detection. For spoken language, a listener is expected to not only detect the occurrence of a sound but also to categorize, differentiate, and comprehend the heard information. ERPs have been used to examine these advanced stages of auditory processing in normal hearing populations (e.g., Kutas and Hillyard, 1980a) and may offer additional insights into auditory abilities of cochlear implant users. Therefore, the purpose of this case study is to examine changes in various levels of auditory processing in a child who received bilateral cochlear implants sequentially.

To develop a better understanding of the impact of bilateral cochlear implants on daily functioning, we chose to assess a basic ability to differentiate brief speech sounds and more advanced skills associated with comprehension of spoken words. In contrast to previous studies, we used a set of speech syllables varying in place of articulation for initial consonants as well as more complex stimuli in the form of monosyllabic words. The logic for this approach stems from the assumption that the human brain is highly adaptive and that even in the context of imperfect auditory input, the brain may find new ways to process such information (e.g., utilize contextual cues) to result in better behavioral outcomes. In other words, one may not be able to hear the difference between /b/ and /d/ sounds perfectly but may be able to easily differentiate the words *big* from *dig*.

METHODS

Participants

Cochlear Implant Participant

The participant was one of a pair of twin sisters with the diagnosis of profound sensorineural hearing loss in both ears, identified at 12 mo of age. The twins were born at 35 wk gestation with no significant birth or medical history. Etiology of hearing loss is unknown (family history includes a cousin with bilateral sensorineural hearing loss).

The participant received a cochlear implant (Nucleus 24) in the right ear at the age of 28 mo. She underwent revision surgery due to lack of progress at the age of 42 mo. The left ear remained unaided until the age of 6 yr, 8 mo (80 mo), when she obtained a second cochlear implant (Cochlear Freedom).

Until 4 yr of age, the participant was enrolled in a simultaneous communication (sign language and spoken English) early intervention program that included both group and individual therapy. At 5 yr of age, the participant enrolled in a private auditory-oral school.

The participant was right-handed as determined using a child variant of the Edinburgh Handedness inventory (Oldfield, 1971) and had normal vision (screened prior to the first test using a Snellen chart). All aided thresholds were verified audiometrically prior to testing and found to be adequate for recognition of the auditory stimuli presented in the study at 75 dB SPL (A).

Normal Hearing Group

Control participants (n = 5, 3 females) were between 3 and 6 yr of age (M = 4.6 yr, SD = .87 yr) and were part of a larger study on auditory processing in cochlear implant users. Hearing thresholds were verified audiometrically prior to testing and were at or better than 20 dB HL bilaterally. All children in this group were right-handed (Oldfield, 1971) and had normal vision (screened using a Snellen chart).

While the age range of the normal hearing children is somewhat wide, the diversity of the group was thought to provide a better approximation of the potential range of auditory processing abilities in the implant user. Because auditory development includes experience-dependent components, previous studies recommend matching implant users to normal hearing participants based on hearing age (i.e., years of experience with sound) rather than on chronological age (Eggermont and Ponton, 2003). Given the history of the implant user (e.g., relatively late first implantation, revision surgery, etc.), the exact hearing age was difficult to determine, but the normal hearing group covered the entire possible range.

MATERIALS

Speech-Sound Discrimination Task

Computer-generated speech-sound stimuli included four consonant-vowel syllables (/ba/, /bu/, /ga/, /gu/) digitized by Bell Labs and controlled for a range of acoustic properties (Stevens and Blumstein, 1978). The initial consonant transition for each syllable was 50 msec in duration followed by a 250 msec steady-state vowel. Each syllable was composed of five formants. Consonant differences were associated with the rising versus falling second formant transition. The first and third formants of both initial consonants contained initial rising components for the two syllables. Rise and decay times were equivalent across all sounds. These speech sounds have been shown to be reliably discriminated by normal hearing adults and children (Molfese, 1978; Molfese et al, 1985; Kraus et al, 1993).

Word-Recognition Task

Digitized spoken words *(bird, bus, car, cat, dog, duck)* from consonant-nucleus-consonant (CNC) word lists (Peterson and Lehiste, 1962) were used for the word-recognition task during ERP testing. These words were chosen because of their high frequency of usage in daily life and because their onset consonants (/b/, /c/, /d/) are similar to the sounds used for the speech-sound discrimination paradigm. Visual stimuli depicting corresponding objects were selected from the standardized set of black-and-white line drawings (Snodgrass and Vanderwart, 1980).

Electrodes

A high-density array of 128 Ag/AgCl electrodes embedded in soft sponges and arranged into a net (Geodesic Sensor Net, EGI Inc., Eugene, OR) was used to record ERPs. Prior to application, the net was soaked in warm saline (KCl) solution, which facilitated transmission of electrical signals from the scalp to the electrodes. The net design allowed for fast electrode application (10 sec to place, under 10 min to adjust position and impedances) and increased participant comfort and compliance as no skin abrasion or gel was required. Impedances remained below 40 kΩ during the testing. Filters were set to 0.1–30 Hz, and data were sampled at 250 Hz. All electrodes were referenced to Cz during recording and later rereferenced to an average reference for data analysis.

PROCEDURES

Audiological Behavioral Testing

Pure-tone thresholds using a modified Hughson and Westlake procedure and aided speech reception thresholds (SRT) were obtained in the soundfield. Speech recognition was completed using clinic protocols at 0° azimuth at 70 dB SPL and included a closed set speech task (NU-CHIPS; Katz and Elliott, 1978), open set word task (PBK word lists; Haskins, 1949), and sentence recognition in quiet (*Hearing in Noise Test-Children* [HINT-C]; Nilsson et al, 1996). All testing was done in the audiology clinic as a part of the routine clinical procedure prior to activation of the second cochlear implant and at 2, 4, and 7 mo postactivation.

Electrophysiological Testing

For the cochlear implant user, administration of all tasks occurred before activation of the second cochlear implant (unilateral stimulation) and at 2, 4, and 6 mo postactivation (bilateral stimulation). On each day of data collection the Ling Six Sound Test (Ling, 2003), which references sounds from across the speech spectrum, was conducted to verify proper functioning of the participant's cochlear implant(s).

Because scalp-electrode connections were established via saline rather than gel, the external parts of the participant's implant(s) were disconnected prior to the application of the sensor net, encased in several overlapping layers of household plastic wrap that served as a moisture barrier (while keeping the microphone opening unobstructed), and then reconnected by threading the magnet through the net and then placing the ear hook/processor on the outside of the sensor net while maintaining its typical position and orientation relative to the ear.

Normal hearing participants completed a single testing session to provide a reference data set reflecting the state of a typically functioning auditory system with similar duration of auditory stimulation as experienced by the implant user.

For all participants, ERPs were recorded in a sound-treated testing room in response to two tasks: a speech-perception task and a word-recognition task employing a match/mismatch visual paradigm. According to the

Table 1. Audiological Test Results

Aided Audiograms (dB HL)	Stimulation	500 Hz	1000 Hz	2000 Hz	4000 Hz	SRT
Pre-activation	Right	40	30	30	35	40
2 mo postactivation	Left	25	35	35	35	35*
	Right	25	25	20	25	
4 mo postactivation	Bilateral	25	25	20	40	30
7 mo postactivation	Bilateral	20	15	20	20	15

*Speech reception threshold (SRT) obtained bilaterally 2 mo postactivation.

procedures routinely used with normal hearing participants, auditory stimuli were presented at 75 dB SPL (A) as measured at the ear from a speaker positioned approximately 1.5 m over the midline of the participant's head. The participant's typical user program settings for her cochlear implant(s) were used during testing to best approximate daily auditory experiences. Stimulus presentation was controlled by E-prime (PST, Inc., Pittsburgh, PA). Continuous EEG was acquired using NetStation v 4.1 (EGI, Inc., Eugene, OR).

Speech-Perception Task

The participants were asked to listen to spoken syllables. The four stimuli (/ba/, /bu/, /ga/, /gu/) were presented in random order for a total of 120 trials (30 trials per stimulus). Inter-stimulus interval (ISI) varied randomly between 1800 and 2800 msec to prevent habituation. To reduce any motion-related artifacts, participants were given the option of watching a silent video. The entire recording session lasted approximately 10–12 min.

Word-Recognition Task

To ensure a participant's ability to complete the task, knowledge of the stimulus words was verified using a picture-pointing task administered prior to the first ERP session. A research assistant spoke each of the words one at a time, and the child was asked to point to the picture depicting the corresponding object.

During the ERP recording, participants were asked to listen to a spoken word, then view a picture on the computer screen, and decide silently whether it matched the word. Each trial began with a 500 msec presentation of a fixation point followed by the auditory stimulus (300–400 msec). After an onset-to-onset delay of 600 msec, a visual stimulus was presented for 2000 msec on a monitor placed approximately 80 cm in front of the participant. ISIs varied between 1800 and 2800 msec. The matching and mismatching word-picture pairs were presented in random order, 30 times each. The recording session lasted approximately 10 min. No overt responses were required of the participants during this task.

The order of the tasks was counterbalanced across participants and across the four testing sessions for the cochlear implant user. During each session, a researcher monitored the participant's behavior, and stimulus presentation was suspended during periods of motor activity or inattention.

ANALYSIS

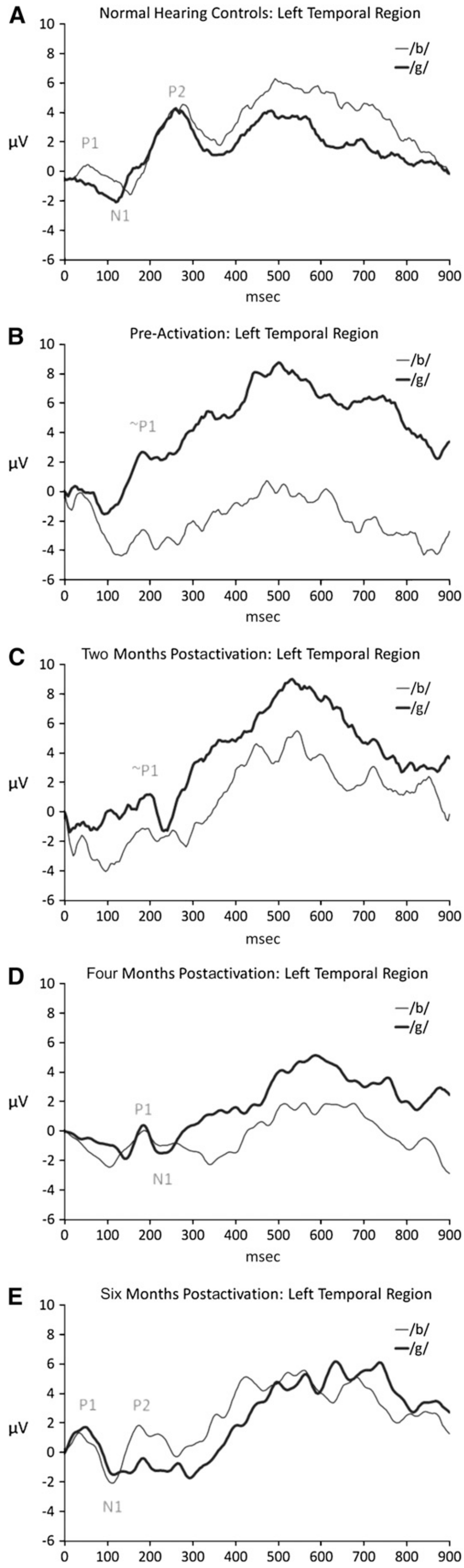
Data Processing

ERP Data

ERP data was segmented into epochs including a 100 msec prestimulus baseline and a 900 msec poststimulus interval. ERPs contaminated by motor activity and eye artifacts were excluded from the analyses using standard artifact rejection procedures. Trial retention rates remained comparable across stimulus conditions (a minimum of 10 artifact-free trials were required for a data set to be included in the analyses). The CI transmitter(s), being an electrical device, generated artifacts in the electrodes adjacent to the magnetic coils. However, the high number of recording electrodes and their even spacing across the scalp allowed to reconstruct data from channels contaminated by artifacts using spherical spline interpolation procedures (Junghofer et al, 2000; see also Singh et al, 2004 for other methods of implant artifact correction). For a trial to be included in the final data set, no more than 15 channels (12% of the array) could be interpolated. Next, the data from individual trials were averaged within each condition, rereferenced to an average reference, and baseline corrected by subtracting the average microvolt value across the prestimulus interval from the poststimulus segment.

Table 2. Speech Perception Test Results

Aided Speech Perception (% Correct)	Stimulation	NU-CHIPS	PBK	HINT-C
Pre-activation	Right	92%	68%	20%
2 mo postactivation	Bilateral	92%	DNT	—
4 mo postactivation	Bilateral	96%	60%	61%
7 mo postactivation	Bilateral	96%	78%	54%



To reduce the number of variables, 128 electrodes were clustered into 10 regions by averaging the data for electrodes within five anatomical regions in each hemisphere: frontal, central, parietal, occipital, and temporal. This approach reflects anatomically based boundaries and has been successfully used in previous studies (Mayes et al, 2005; Key et al, 2006).

For the purpose of the case study, the waveforms were visually examined for morphology and amplitude or latency differences between the conditions, and the results of ERPs recorded with bilateral stimulation were compared to those from the unilateral recording obtained prior to the activation of the second implant. Additionally, the ERPs of the cochlear implant user were compared to those from a group of five normal hearing children of similar hearing age.

RESULTS

Audiological Behavioral Testing

Information on the cochlear implant user's pure tone thresholds and speech recognition pre–bilateral cochlear implant activation as well as data obtained 2, 4, and 7 mo post–initial activation are presented in Tables 1 and 2. Pure tone average (PTA) in the right ear prior to the activation of the bilateral implant was 33 dB HL. By 7 mo of use with bilateral cochlear implants, PTA was 18 dB HL. Speech reception threshold (SRT) results were consistent with the pure tone findings for all test intervals. There was a slight improvement in the open set monosyllabic speech recognition scores, but it was not considered to be significant (Thornton and Raffin, 1978). The participant's HINT-C sentence recognition score showed improvement by 41% after only 4 mo of using bilateral cochlear implants. Though HINT-C performance decreased by 7% at testing 7 mo postactivation, this could be a reflection of the sentence list used.

ERP Results

Speech-Sound Task

Following previous findings reported in normal hearing populations, indicating that processing of place of articulation characteristics is typically reflected over temporal sites in the left hemisphere (Molfese et al, 2005), our examination of the data was limited to that location. An averaged waveform for consonant sounds revealed the typical P1-N1-P2 response in the control

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Figure 1. Averaged ERPs to consonant sounds /b/ and /g/ recorded at the left temporal sites in normal hearing children *(A)* and a cochlear implant user *(B–E)*.

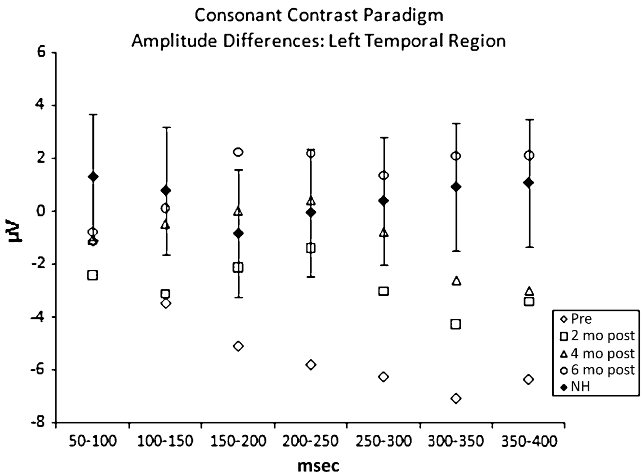


Figure 2. Mean differences in amplitudes in response to /b/ and /g/ sounds measured in 50 msec intervals between 50 and 400 msec.

group with sound discrimination evident mainly in amplitude differences of the peaks (Figure 1A). Note that the waveforms for the control group show reasonably low variability despite a relatively wide age range as reflected in narrow, well-defined peaks.

ERPs of the cochlear implant user demonstrated amplitude differences between the sounds but did not have the same morphology as was observed in normal hearing children. Prior to activation of the second cochlear implant, waveforms of the implant user appeared immature as they lacked complexity and consisted only of the initial negativity followed by a broad positivity (Figure 1B). At 2 mo after activation of the second implant, there were no clear improvements in waveform morphology (Figure 1C) despite the presence of bilateral auditory inputs. At 4 mo postactivation, the ERPs began to increase in complexity as reflected in detectable P1-N1 (Figure 1D). At 6 mo, a P1-N1-P2 complex was clearly present (Figure 1E). Interestingly, at that time the P2 response of the CI user appeared to occur at a slightly earlier latency than in the normal hearing group, possibly due to the accelerated maturation rate as a result of increased auditory input and/or the mode of sound input (faster electrical vs. slower mechanical/hydraulic).

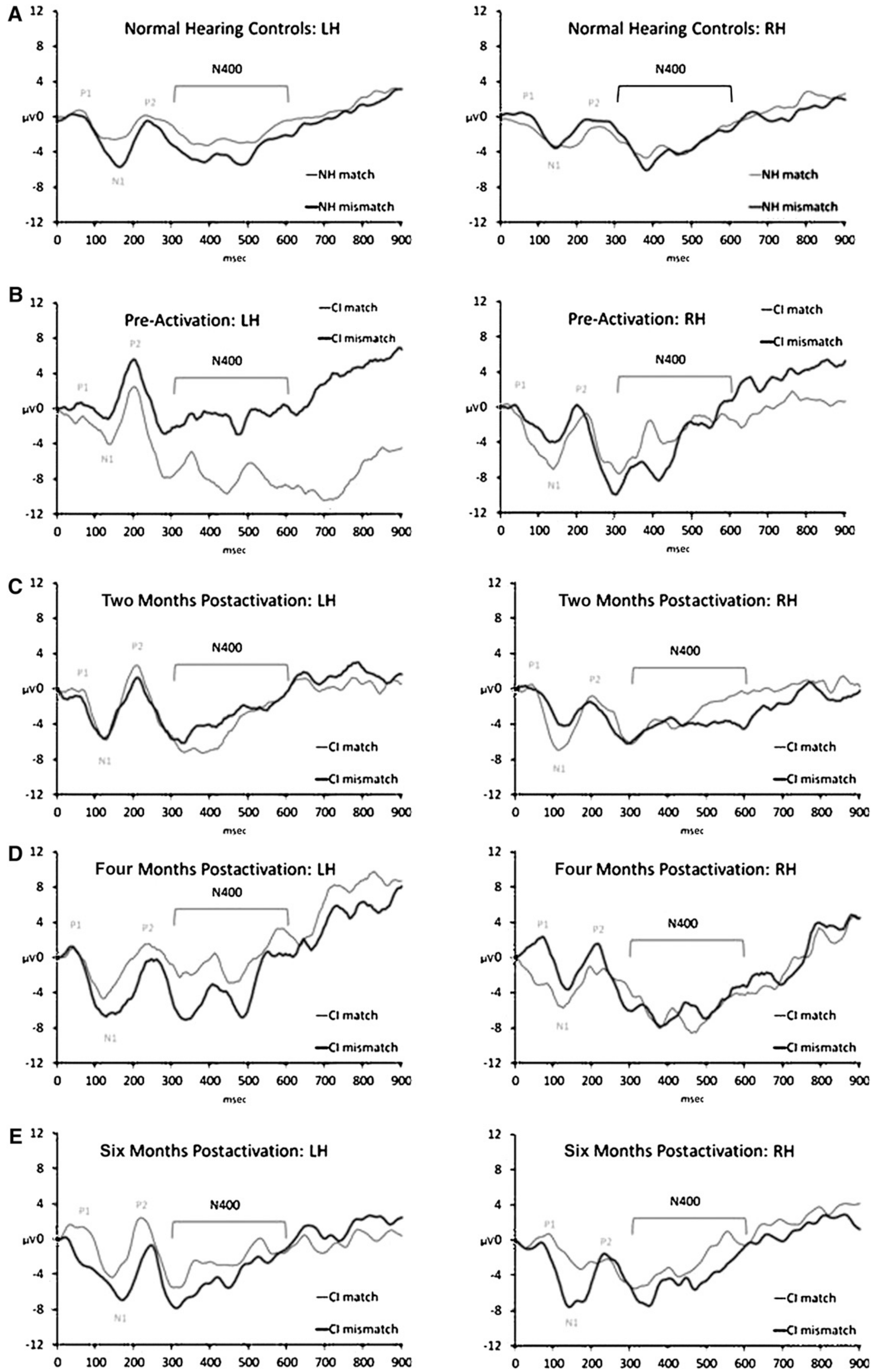
To better quantify the participants' ability to hear differences between the speech sounds, mean differences in amplitudes in response to /b/ versus /g/ sounds were measured in 50 msec intervals within 50–400 msec to encompass the P1-N1-P2 complex while accounting for possible processing delays in the CI user. Mean amplitude values were chosen over the traditional peak amplitude measures to minimize potential issues associated with the subjective nature of peak picking (see Luck, 2005). As demonstrated in Figure 2, the largest differences in ERPs to the two sound groups in the normal hearing children were observed between 50–150 msec and 300–400 msec. These values are consistent with differences seen in the P1-N1-P2 complex (Figure 1). For the CI user, in the unilateral condition, sound discrimination was evident from 100 msec throughout the analysis window. Following activation of the second implant resulting in the bilateral auditory input, the difference values progressively began to approximate those observed in the normal hearing group (i.e., fall within 1 SD) in size and by 6 mo in the direction of the differences. However, at 6 mo the onset of initial sound discrimination appeared to be delayed compared to the normal hearing group.

Word-Processing Task

In line with previous studies using similar paradigms (e.g., Miles and Stelmack, 1994), our examination of waveforms was focused on the anterior N400 response, which has been identified as sensitive to the semantic relationship between word and picture components of a trial (e.g., Ganis et al, 1996). The anterior N400 was expected to occur between 300 and 600 msec after picture onset and be larger (more negative) in response to images that did not match the preceding spoken word. This response represents a variant of the classic N400 first reported by Kutas and Hillyard (1980b) in response to semantically incongruent ending words of visually presented sentences. A similar response can also be observed when the last word of the sentence is replaced by a picture (Ganis et al, 1996). The N400 congruity effect for sentences tends to be largest at posterior sites, but the response tends to be at its maximum at anterior sites for pictures (see also Holcomb and McPherson, 1994; Knott et al, 1998).

Additionally, several studies report posterior positive ERP responses sensitive to match/mismatch between the two stimuli in a trial reflected in greater positive amplitudes for incongruent pairings around 500 msec after stimulus onset (Pratarelli, 1994; Simos and Molfese, 1997). Unlike the lexical and semantic relatedness reflected by the N400 response, the P500 effect is thought to reflect confirmation of participant's subjective expectancies regarding the second stimulus in a trial (Gratton et al, 1990). P500 is also referred to as a late positive component (LPC) and typically occurs within 300–600 msec after stimulus onset. Reduced posterior positivity within this range may also indicate reduced subjective confidence in their performance on the task (Johnson, 1986; Knott et al, 1998).

Examination of the grand-averaged waveforms suggests that prior to bilateral cochlear implant activation, the participant's auditory comprehension was delayed relative to the normal hearing controls. This is reflected in the ERP differences to differing visual stimuli (i.e.,


A
Normal Hearing Controls: LH
Normal Hearing Controls: RH
N400
P1
P2
N1
NH match
NH mismatch
B
Pre-Activation: LH
Pre-Activation: RH
CI match
CI mismatch
C
Two Months Postactivation: LH
Two Months Postactivation: RH
D
Four Months Postactivation: LH
Four Months Postactivation: RH
E
Six Months Postactivation: LH
Six Months Postactivation: RH
µv0
msec
0 100 200 300 400 500 600 700 800 900
12 8 4 -4 -8 -12

those that match and do not match the preceding spoken word). This is especially of concern as the stimulus words were high-frequency words, known by all participants for an extended period of time.

Anterior N400

Similar to findings reported by Miles and Stelmack (1994), in normal hearing controls, an N400 response to pictures not matching the preceding spoken word was evident over both left and right anterior scalp locations with larger amplitude over the left hemisphere (Figure 3A). In the unilateral condition (prior to the activation of the second cochlear implant), a similar N400 response appeared to be present over the right hemisphere (ipsilateral to the first implant) while over the left hemisphere the direction of the effect was reversed with larger amplitudes for matching stimuli (Figure 3B). At 2 mo postactivation, the left N400 was still reversed, although the overall waveform morphology was closer to that of the normal hearing participants (Figure 3C). After 4 mo of bilateral experience, the N400 effect became more prominent over the left hemisphere than the right hemisphere, suggesting reorganization in brain sources of the semantic processing. By 6 mo, the semantic mismatch response was evident over both hemispheres, indicating that the participant was able to process the spoken words and to create a semantic context for the following pictures at the speed similar to that of normal hearing children (Figures 3D–E).

Posterior P500

Increased posterior positivity was observed in response to pictures not matching the preceding spoken word over both hemispheres in normal hearing controls around 500 msec after stimulus onset (Figure 4A). Prior to the activation of the second cochlear implant, this response was absent in the implant user (Figure 4B) but began to emerge bilaterally as early as 2 mo postactivation (Figure 4C). The P500 response became more clearly apparent over the right hemisphere after 4 mo of bilateral experience (Figure 4D). At 6 mo postactivation, the expected match/mismatch response was evident over both hemispheres, and the overall waveform shapes resembled those of the normal hearing controls (Figure 4E).

Using the same approach as in the speech-sound task, difference values were calculated for mean N400 (300–500 msec) and P500 (400–600 msec) amplitudes over anterior and posterior scalp regions, respectively (Figure 5). Over time, condition differences observed in the ERPs of the CI user began to closely resemble those of the normal hearing control group. For the anterior N400, unilateral auditory stimulation appeared to be not entirely sufficient to create contextual expectations for the visual images as matching rather than mismatching pictures were associated with more negative amplitudes (Figure 5A). Experience with bilateral stimulation resulted in waveforms consistent with the control group for contextual processing, most likely due to the increased speed of semantic processing due to reduced effort exerted at the phonological analysis stage. Matching stimuli elicited higher amplitudes than mismatching stimuli for the posterior P500 response in the unilateral condition, suggesting potentially reduced confidence in mismatch identification (Figure 5B). However, by 6 mo post–bilateral-activation, the direction of the differences reversed, and their magnitude closely matched that of the control group.

DISCUSSION

The purpose of this study was to examine changes in auditory processing after acquisition of a second cochlear implant in an experienced unilateral cochlear implant user. Although this participant may be considered, by some, a less than optimal candidate for a bilateral cochlear implant given the prolonged duration of deafness in the second ear (which remained unaided until a few months prior to the acquisition of the second implant), our evidence demonstrates clear benefits of the addition of the second cochlear implant as reflected in improvements in auditory processing over the first 6 mo of bilateral experience.

Audiologically, comparison of the test results obtained after 4 yr of unilateral implant use (prior to the activation of the second cochlear implant) and at 7 mo of bilateral experience revealed expected improvements in pure tone thresholds and speech-perception tests administered in quiet. These results suggest better auditory detection abilities for softer sounds, which can lead to reduced listening effort (Hicks and Tharpe, 2002).

A subjective report of oral communication abilities highlights some of the possible benefits of improved auditory experiences. As a unilateral cochlear implant user, the participant used simultaneous communication including signs and spoken language, but reported a preference for oral communication. After 15 mo in an auditory-oral school, where no sign language was used, this child successfully used expressive and receptive

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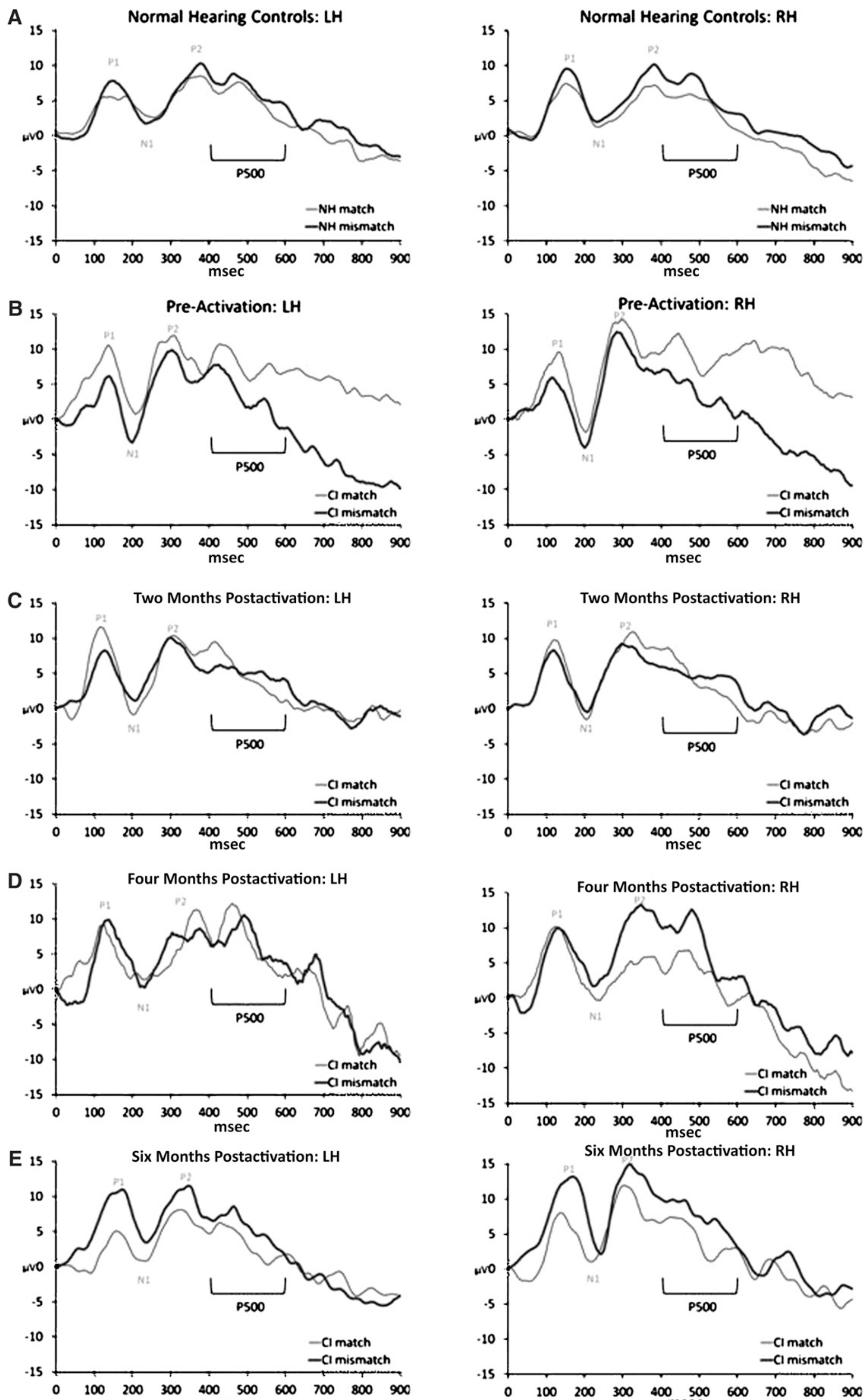
Figure 3. Averaged ERPs over anterior scalp regions in responses to pictures matching and not matching preceding spoken word in normal hearing children *(A)* and a cochlear implant user *(B–E).*



A
Normal Hearing Controls: LH
Normal Hearing Controls: RH
NH match
NH mismatch
B
Pre-Activation: LH
Pre-Activation: RH
C
Two Months Postactivation: LH
Two Months Postactivation: RH
D
Four Months Postactivation: LH
Four Months Postactivation: RH
E
Six Months Postactivation: LH
Six Months Postactivation: RH
CI match
CI mismatch
P1
P2
N1
P500
µV0
msec

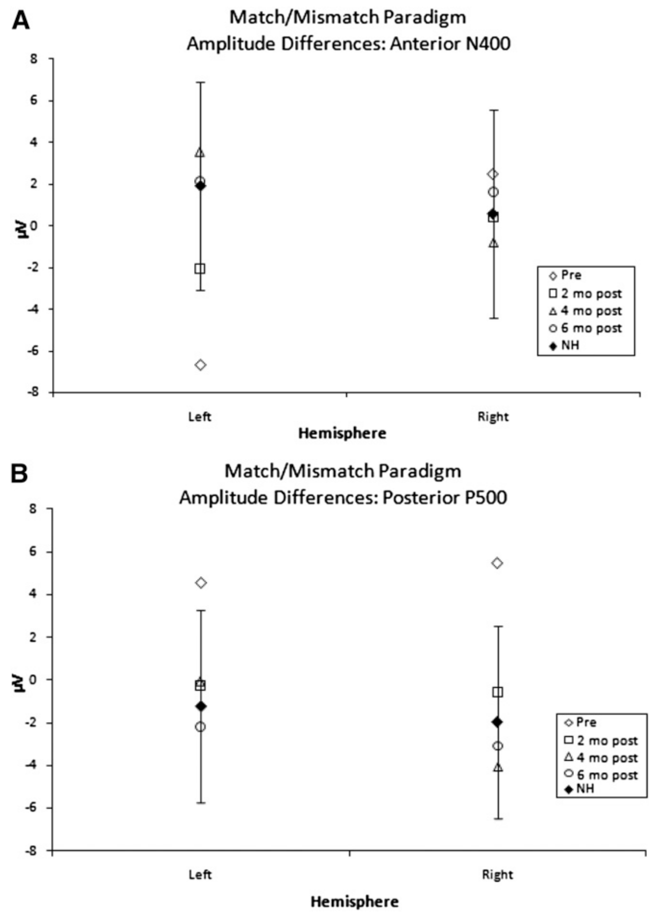


Figure 5. Mean differences in amplitudes in response to matching and mismatched auditory and visual stimuli over anterior scalp regions within the 300–500 msec range *(A)* and posterior scalp regions within the 400–600 msec range *(B)*.

communication primarily only with familiar listeners. Approximately 4 mo after the participant began to use both cochlear implants, parents and teachers noted that unfamiliar listeners were able to better understand the participant, and the child appeared happier and more at ease at school and reported less fatigue during the day.

Examination of the results from behavioral assessments revealed that observed improvements in auditory functioning were not uniform. Performance on an open-set word-recognition task (PBK) showed small, but not significant, improvement after 7 mo of bilateral experience even though the participant was more engaged and easier to test. One possible explanation for limited increase in PBK scores could be related to speech intelligibility issues; however, it is also possible that the child's open-set word recognition did not significantly improve by 7 mo postactivation. Interestingly, findings from ERP studies in normal-hearing children demonstrate that efficient speech-sound processing is one of the fundamental abilities needed for a range of speech and language skills. Group differences in ERPs to speech sounds for high and low performing children can be present years before any behavioral differences become apparent (Molfese and Molfese, 1997; Espy et al, 2004).

Though improvement on single-word tasks was limited, overall performance on sentence recognition showed a notable increase. As a unilateral cochlear implant user, the participant was able to repeat the noun or subject of a sentence. By the fourth month of bilateral experience, sentence recognition scores increased by nearly threefold as the participant's recognition and reproduction of sentences improved. The discrepancy between the participant's performance on the word- and sentence-level tasks could be due to differences in the difficulty level. Single word processing is more challenging as it lacks any facilitation

←

Figure 4. Averaged ERPs over posterior scalp regions in responses to pictures matching and not matching preceding spoken word in normal hearing children *(A)* and a cochlear implant user *(B–E)*.

from the contextual information that would be available in a sentence. As such, it offers a more sensitive measure of improvement in auditory processing over time.

Psychophysiological results complement and extend behavioral findings. Similar to the distribution of the scores from behavioral assessments, improvements in brain processing of auditory information were also not uniform. As an experienced unilateral cochlear implant user, the participant's brain was not very efficient at processing individual speech sounds or more complex word stimuli as reflected in the absence of expected ERP responses observed in normal hearing controls. However, acquisition of the second cochlear implant at almost 7 yr of age appears to have resulted in an increased ability to process auditory input despite the long history of deafness in the unaided ear. The P1-N1-P2 complex for speech sounds (i.e., /ba/, /bu/, /ga/, /gu/) was similar to that of the normal hearing controls by 6 mo of bilateral experience. These results are consistent with improvements in auditory performance documented behaviorally at 7 mo postactivation.

It is possible that the observed changes in ERP waveforms reflect typical maturational effects rather than the increased processing due to the bilateral stimulation following the acquisition of the second implant. A future replication study with larger samples and repeated testing for both patient and control groups will provide a definitive answer to this question. Specifically, grouping children who receive both implants by 3.5 yr of age (Sharma et al, 2002a, 2002b) and those with longer interimplant delays will allow for an examination of a delay in sequential implantation. In the meantime, the existing data examining stability of the auditory P1-N1 responses to speech in normal hearing children report high test-retest reliability across weeks (Uwer and von Suchodoletz, 2000) and months (Raikkonen et al, 2003). Also, previous ERP studies tracking auditory development following unilateral implantation report most changes to occur within the first year of implant use (Jordan et al, 1997; Sharma et al, 2002a, 2002b). Therefore, in the context of the participant's extensive experience with the unilateral implant (3+ yr) and reasonable month-to-month stability of the P1-N1 responses reported in normal hearing children, we interpret major changes in waveform morphology observed for the implant user to more likely reflect functional rather than purely age-related improvements.

The ERP results from the speech-sound task provide additional explanation for the PBK scores. The ability to hear differences between speech sounds quickly and efficiently is necessary for the ability to accurately reproduce them, resulting in better intelligibility of speech. In ERPs, the P2 peak is sometimes thought to reflect stimulus classification processes (Garcia-Larrea et al, 1992), and compared to the normal hearing controls, the P2 response of the cochlear implant user was typically not detectable, but when present, small in amplitude. A less pronounced P2 may reflect less than optimal processing of sound details, which in turn may lead to less than accurate sound production, thus resulting in poor speech intelligibility. This might be evidence for contribution of speech production issues leading to a clinical misinterpretation of spoken responses.

Unlike the assessments of word processing that require an oral response and thus can be confounded by poor speech intelligibility or by lack of participant motivation or cooperation, a passive paradigm using ERPs to document word processing could reveal greater improvements in comprehension. Indeed, our findings demonstrated that as a unilateral cochlear implant user, the participant was able to process word-level stimuli, but not as efficiently as normal hearing children as reflected in the absence of the left anterior N400 and posterior P500 responses in the typical time ranges. However, after 4 mo of bilateral stimulation, the participant's previously missing ERP responses began to develop, and at 6 mo, the ERP waveforms were nearly identical to those of the controls, reflecting markedly improved speed of word comprehension and increased utilization of comprehended information. These results are consistent with the pattern of performance on HINT-C sentences in quiet.

In sum, although obtained in a single pediatric user and therefore needing replication with a larger sample of sequentially implanted bilateral implant users, our findings lead to two main conclusions. First, bilateral cochlear implantation is a viable option for children who already have one cochlear implant and are auditory learners, even if the other ear has remained unaided for an extended period of time. Prior studies reported that bilateral performance on speech-perception tests correlated with age of implantation and duration of deafness in the later-implanted ear (Steffens et al, 2008; Wolfe et al, 2007). This study, however, suggests that even in a less than optimal candidate, bilateral implantation leads to improvements in auditory processing, sentence recognition, and in general quality of life within 6 mo after activation of the second implant (see also Dinces et al, 2009 for evidence of benefits following late unilateral implantation). Second, extending standard assessments of the auditory development associated with cochlear implants to include a wider range of auditory stimuli may be beneficial for documentation of central processing and behavioral changes associated with improved auditory experience. In addition to recording ERPs to clicks, tones, and single syllables, we suggest broadening the range of paradigms currently used to track progress in cochlear implant users to include syllable discrimination and word-level processing. Our findings demonstrate that after the brief 6 mo period of bilateral experience, the improvements in word comprehension outpaced those in syllable discrimination, most likely due to the possibility of increased availability of binaural cues combined with contextual information. Because single syllables were presented out of context, improvements in processing of such information would be slower, and thus not fully represent the extent of auditory functioning.

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