Neurophysiology of Cochlear Implant Users II: Comparison Among Speech Perception, Dynamic Range, and Physiological Measures

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Objective: **The overall objective of this study was to relate electrically evoked potentials recorded from different levels of the auditory pathway with behavioral measures obtained from adult cochlear implant subjects. The hypothesis was that adult recipients of cochlear implants who have open-set speech perception and those recipients with no open-set speech perception would differ in their neurophysiologic responses recorded at one or more levels of the auditory pathway.**

Design: **The subjects were 11 adults implanted with the Clarion cochlear implant. The electrical auditory brainstem response (EABR, Wave V), electrical auditory middle latency response (EAMLR, Na-Pa complex), and the electrical late auditory response (ELAR, N1-P2 complex), were recorded from three intra-cochlear electrodes. The stimuli used to record the evoked potentials varied in rate and amplitude. Behavioral measures (between threshold and upper limit of comfortable loudness) were used to define the subject's dynamic range at the different stimulus rates. Word and sentence recognition tests evaluated subjects' speech perception in quiet and noise. Evoked potential and behavioral measures were examined for statistical significance using analysis of variance for repeated measures and correlational analyses.**

Results: **Subjects without open-set speech recognition demonstrated 1) poorly formed or absent evoked potential responses, 2) reduced behavioral dynamic ranges, 3) lack of change in the size of the dynamic range with a change in stimulus rate, and 4) longer periods of auditory deprivation. The variables that differentiated the best performers included 1) presence of responses at all three levels of the auditory pathway, with large normalized amplitudes for the EAMLR, 2) lower evoked potential thresholds for the Na-Pa complex, 3) relatively large dynamic ranges, and 4) changes in the size of the dynamic range with changes in stimulus rate.**

Conclusions: **In this study, the inability to follow changes in the temporal characteristics of the stimulus was associated with poor speech perception performance. Results also illustrate that variability in speech perception scores of cochlear implant recipients relates to neurophysiologic responses at higher cortical levels of the auditory pathway. Presumably, limited neural synchrony for elicitation of electrophysiologic responses underlies limited speech perception. Results confirm that neural encoding with electrical stimulation must provide sufficient physiologic responses of the central nervous system to perceive speech through a cochlear implant.**

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In the normal ear, sound produces a traveling wave that causes the hair cells of the inner ear to be stimulated. The activation of hair cells elicits neural discharge of auditory nerve fibers. A cochlear implant bypasses this level of sound processing and activates auditory nerve fibers directly, followed by the transmission of impulses to the central auditory pathway (Abbas, 1993; Kiang & Moxon, 1972; Loeb, White & Jenkins, 1983). The primary ascending central auditory connections include the cochlear nuclei, inferior colliculus, and medial geniculate bodies of the thalamus. Neurons terminate in the primary auditory cortex located in the temporal lobe of the brain (Webster, Popper, & Fay, 1992). Processing of sound involves the peripheral and central auditory system for all listeners, including cochlear implant users.

Cochlear implantation is a treatment option for adults and children with bilateral severe-to-profound sensorineural hearing loss who do not benefit from traditional amplification. Over the years, investigators have reported on the speech recognition abilities of adults using cochlear implant devices (Bilger, 1977; Blamey & Clark, 1990; Eddington, 1980; Schindler & Kessler, 1993; Skinner et al., 1991; Staller et al., 1997; Tyler, Moore, & Kuk, 1989; Wilson, Finley, Lawson, Wolford, Eddington, & Rabinowitz, 1991) or children using similar devices (Berliner, Tonokawa, Dye, & House, 1989; Cowan et al., 1997; Dowell et al., 1991; Fryauf-Bertschy,

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Tyler, Kelsay, & Gantz, 1992; Fryauf-Bertschy, Tyler, Kelsay, Gantz, & Woodworth, 1997; Geers & Moog, 1991; Osberger et al., 1991; Sehgal, Kirk, Svirsky, & Miyamoto, 1998). Most patients demonstrate improved performance when compared with their pre-implant abilities. Although there is wide variation in performance, many multichannel cochlear implant users understand words and sentences with their hearing alone and can communicate with others over the telephone.

Factors that may contribute to the variability in word and sentence recognition abilities of cochlear implant users include subject characteristics, psychophysical measures, device characteristics, and neurophysiologic differences. More specific factors that might account for variation in performance across patients are the extent of neural survival (Jyung, Miller, & Cannon, 1989; Shepherd, Clark, & Black, 1983; Walsh & Leake-Jones, 1982), properties of the auditory nerve such as the ability to recover from a refractory state (Brown, Abbas, Borland, & Bertschy, 1996; Brown, Abbas, & Gantz, 1990; Stypulkowski & van den Honert, 1984), the influence of sensory deprivation on neurophysiological development (Leake, Hradek, Rebscher, & Snyder, 1991; Lousteau, 1987; Trune, 1982), spatial and temporal resolution abilities (Shannon, 1983; Zeng & Shannon, 1994), and the integrity of the central auditory pathways (Kraus et al., 1993b; Micco et al., 1995; Oviatt & Kileny, 1991; Stypulkowski, van den Honert, & Krivstad, 1986). To date, however, variability in performance across patients is not clearly understood.

Auditory evoked potentials are electrical potentials recorded from the scalp and form a sequence of peaks and troughs after the onset of an electrical stimulus. They are often described by the time epoch within which they occur. Early latency responses occur within 0 to 10 msec of an abrupt stimulus onset and reflect activity from the eighth nerve and brainstem (Davis, 1939; Jewett & Williston, 1971; Møller & Jannetta, 1985). Middle latency responses occur between 10 to 50 msec of stimulus onset and reflect activity from the thalamo-cortical pathways (Geisler, Frishkopf, & Rosenblith, 1958; Kraus, Smith, & McGee, 1987; Picton, Hillyard, Krausz, & Galambos, 1974). Long-latency potentials occur beyond 50 msec and have more complex generators that reflect various levels of cortical processing (Cunningham, Nicol, Zecker, & Kraus, 2000; Kraus et al., 1993a; Kraus & McGee, 1992; Näätänen & Picton, 1987; Scherg & von Cramon, 1986; Tremblay, Kraus, McGee, Ponton, & Otis, 2001; Vaughan & Ritter, 1970).

Many of the characteristics of the neural responses elicited by an electrical stimulus can be demonstrated using far-field evoked potentials and have been reported in animals and humans with both experimental implants and FDA-approved devices (Abbas, 1993). Electrical auditory brainstem responses (EABRs) have been used to assess neural integrity, implant function, placement of intracochlear electrode arrays, and programming levels needed for the externally worn speech processor (Abbas & Brown, 1988; Brown, Abbas, Fryauf-Bertschy, Kelsay, & Gantz, 1994; Firszt, Rotz, Chambers, & Novak, 1999; Firszt, Wackym, Gaggl, Burg, & Reeder, Reference Note 1; Gardi, 1985; van den Honert & Stypulkowski, 1986). The recordings of electrical auditory middle latency responses (EAMLRs) have been used to estimate spiral ganglion cell survival, to select an ear for implantation, and to evaluate differences in subject performance (Firszt et al., 1999; Jyung et al., 1989; Kileny, Kemink, & Miller, 1989; Shallop, Beiter, Goin, & Mischke, 1990). Electrically evoked late responses (ELARs), such as the N1, P2, N2, P300 and mismatch negativity (MMN) have been measured to evaluate differences in subject performance related to cortical processing (Kaga, Kodera, Hirota, & Tsuzuka, 1991; Kraus et al., 1993b; Makhdoum, Groenen, Snik, van den Broek, 1997; Micco et al., 1995).

Individuals with poor auditory nerve survival or atrophy of the central auditory nervous system may perform more poorly than those with relatively intact auditory systems (Hall, 1990; Pfingst, Spelman, & Sutton, 1980). We know that speech perception depends on auditory pathway encoding. This encoding depends, in part, on synchronous neural activity. Measures such as evoked potentials allow us to evaluate the critical synchronous components of neural encoding. The variability in speech perception scores of cochlear implant recipients may relate to neurophysiologic responses at one or more levels of the auditory pathway. It is reasonable to expect that by studying a combination of early, middle and late electrically evoked potentials within an individual cochlear implant user, we can better evaluate the extent of neural synchrony from the periphery to the auditory cortex. To date, there have been few published reports of within-subject electrophysiologic recordings that represent the brainstem, midbrain, and cortical areas when elicited with electrical stimulation.

The overall objective of this study was to relate electrically evoked potentials recorded from generator sites along the auditory pathway with behavioral measures in adult cochlear implant subjects. The specific aim was to determine whether the presence and parameters (measures of latency, amplitude, and threshold) of evoked potentials at three levels of the auditory pathway relate to overall speech perception performance. The hypothesis was that adult recipients of cochlear implants who have open-set speech perception and those recipients with no open-set speech perception would differ in their neurophysiologic responses recorded at one or more levels of the auditory pathway. (A companion paper in this issue describes the effects of stimulus level and electrode site on the recording of electrically evoked potentials for this subject sample; Firszt, Chambers, Kraus, & Reeder, 2002.)

METHODS AND PROCEDURES

Subjects

Subjects were 11 adults who received the Clarion CI cochlear implant device and 1.2 radial electrode array and had full electrode insertions. At the time of study, the subjects ranged in age from 29 to 75 yr, with a mean of 56 yr. At the time of cochlear implantation, the subjects ranged in age from 24 to 70 yr, with a mean of 53 yr. Subjects had used their cochlear implants for at least 3 mo, with a maximum length of use of 5 yr and a mean across subjects of 2.7 yr. Subjects were full-time users of their cochlear implants with a range of daily wear between 10 to 15 hr. Additional background information for each subject is provided in a companion paper in this issue (Firszt et al., 2002).

General Procedures

For each subject, sound field detection thresholds were obtained to ensure speech audibility followed by a speech perception evaluation. Behavioral data were collected to define each subject's behavioral dynamic range (BDR) on three medial electrodes that represent apical, mid, and basal locations within the cochlea. The stimuli delivered during the behavioral procedure were at the three rates used for electrophysiologic recording of the EABR, EAMLR, and ELAR. These rates are considerably slower (e.g., 20.03 Hz, 9.3 Hz, 1.1 Hz) than those used when programming the speech processor (833 Hz) but are necessary for optimal electrophysiologic recordings. Each subject's BDR also was determined using the stimulus rate of 833 Hz although the faster rate was not used to record evoked potentials.

Sound Field and Speech Perception Measures: Stimuli, Equipment, and Procedures

Both warble-tone and speech detection thresholds, as well as speech perception abilities, were tested in the sound field. Pulsed warble tones were presented via calibrated sound field equipment in a sound-treated booth. Word and sentence recognition tests included those from the Minimum Speech Test Battery for Adult Cochlear Implant Users (MTSB). The Consonant-Nucleus-Consonant (CNC) Monosyllabic Word Test (Peterson & Lehiste, 1962) assessed single syllable word identification. The lists contain 50 monosyllabic words presented in an open-set format. The presentation of auditory-only sentence lists from the Hearing In Noise Test (HINT) (Nillson, Soli, & Sullivan, 1994) evaluated each subject's ability to understand sentence material in quiet and in the presence of background noise. Two 10-sentence HINT lists were administered in quiet, and two 10-sentence lists were presented in the presence of eight-talker speech babble at a +10 dB signal-to-noise ratio. The City University of New York (CUNY) (Boothroyd, Hanin, & Hnath, 1985) sentences were administered because a large amount of comparative data are available that have been collected with cochlear implant subjects. Two 12-sentence CUNY lists were administered in quiet, and two 12-sentence lists were presented in the presence of eight-talker speech babble at a +10 dB signal-to-noise ratio.

A final measure of speech perception was the Revised Speech Perception in Noise (SPIN) Test (Bilger, 1984; Bilger, Nuetzel, Rabinowitz, & Rzeczkowski, 1984; Kalikow, Stevens, & Elliott, 1977). Each form of the Revised SPIN test contains 50 items, 25 of which are high-predictability sentences and 25 of which are low-predictability sentences. Each of the forms is psychometrically equivalent and balanced for types of syllables, vowels, and consonants. The masking noise consists of 12-talker babble (Kalikow et al., 1977) at a signal-to-babble ratio of +8. All speech stimuli were presented auditory-only at 70 dB SPL. The sensitivity setting of the speech processor was set at a level determined by the subject to be comfortable for listening. Subjects were seated 1 m from the loudspeaker at 0 degree azimuth.

Detection thresholds were obtained in the sound field using pulsed warbled tones at the frequencies 250, 500, 1000, 2000, 3000, and 4000 Hz. Speech detection thresholds were also determined. A standard Hughson-Westlake procedure (Carhart & Jerger, 1959) was administered using 5-dB increments for warbled tones and speech stimuli.

Behavioral Measures: Stimuli, Equipment, and Procedures

Stimuli were biphasic current pulse trains, 75 μsec in duration, at rates of 833 Hz, 20.03 Hz, 9.3 Hz, and 1.1 Hz. Stimulus amplitude was expressed in clinical units (CU) relative to microamperes (μA), and varied between 3 and 3000 CU. (Note: The majority of analyses in this study depend on the stimulus levels that represent proportions of the subject's BDR, rather than the absolute current level. CUs, however, may not be directly comparable across subjects and electrodes due to differences in electrode impedance.) Stimuli were presented through an Ascentia 910 laptop computer connected to a clinician's programming interface unit, a speech processor and a headpiece.

The following paragraphs describe the procedures for the measures of behavioral threshold (BT), most comfortable loudness level (MCL), and upper limit of comfort level (ULCL). For each electrode tested, the order of acquisition was BT, MCL, and then ULCL. The order of electrodes tested was randomized within subjects. For behavioral procedures, subjects used a 10-step loudness scale (Clarion Multi-strategy Cochlear Implant System Manual Version 2.0, 1996).

Subjects listened and identified when a sound was just perceptible (2 on the loudness scale) using an ascending procedure with repeated pulse trains adapted from that described by Skinner, Holden, Holden, and Demorest (1995). Stimuli were pulse trains that started at 3 CU and increased in steps of 10 CU until a response occurred. The signal was decreased 20 CU below this response level, then the first ascending trial was initiated. The stimuli increased in 5 CU steps until the subject responded. The stimulus was decreased 10 CU below this level and the procedure repeated three times. BT was the average of the subject's lowest responses on the four ascending trials.

For MCL and ULCL, testing began at a level below threshold. The stimulus slowly increased between 3 and 5 CU until the subject identified MCL followed by identification of ULCL. The MCL level, defined as comfortably loud on an individual electrode, represented 6 on the loudness scale. The ULCL, defined as the maximum loudness that could be tolerated for several minutes, represented 9 on the loudness scale. This process was replicated twice to obtain a second and third estimation of MCL and ULCL. The average of the three levels judged to be comfortably loud was the MCL value, and those judged as maximum loudness was the ULCL value.

Electrophysiologic Measures

EABR, EAMLR, and ELAR responses were recorded at stimulus levels that corresponded to a) 100%, 75%, 50%, and 25% of the subjects' BDR, b) the evoked potential threshold (EPT), and c) the BT. Details of the recording parameters, procedures, and identification of waveform measurements are summarized in the companion paper of this issue (Firszt et al., 2002).

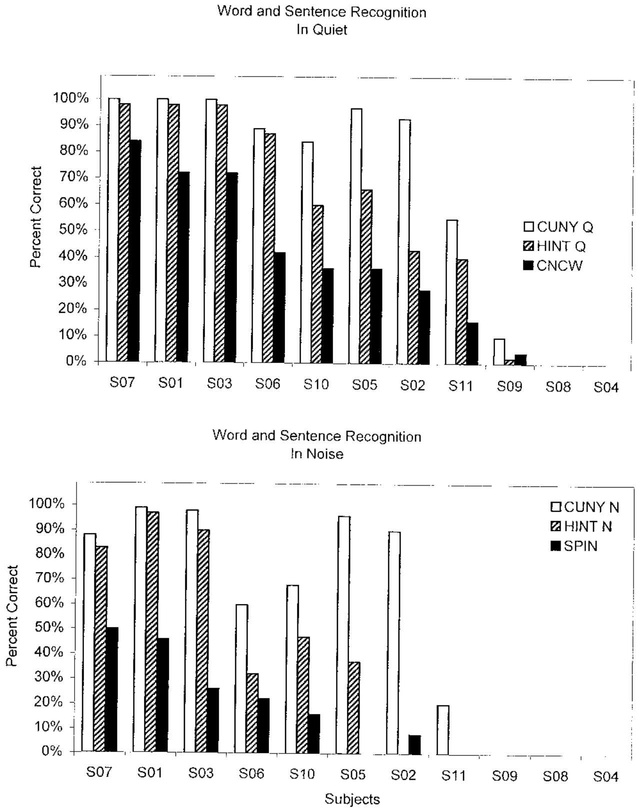

Figure 1. Individual subject word and sentence recognition scores shown for tests administered in quiet (upper panel) and in the presence of background noise (lower panel). Subjects are ordered from highest to lowest performance according to an average across tests after conversion of each test score to a standard score (z).

RESULTS

Sound Field and Speech Perception Measures

Subjects had speech detection thresholds that ranged from 10 to 30 dB HL, which confirmed that speech was audible at a conversational loudness level. The audiometric PTA thresholds (500 Hz, 1000 Hz, 2000 Hz) ranged from 20 to 33 dB HL for 10 of the 11 subjects. Subject 3 had a PTA of 15 dB HL. The mean PTA for the group was 26 dB HL.

Figure 1 displays the speech perception results for individual subjects for the quiet conditions (top panel) and noise conditions (bottom panel). Both panels indicate the percent correct word or sentence recognition obtained by each subject on each test administered. Subjects are ranked from highest to lowest performance within each panel according to a composite score for each subject. The composite

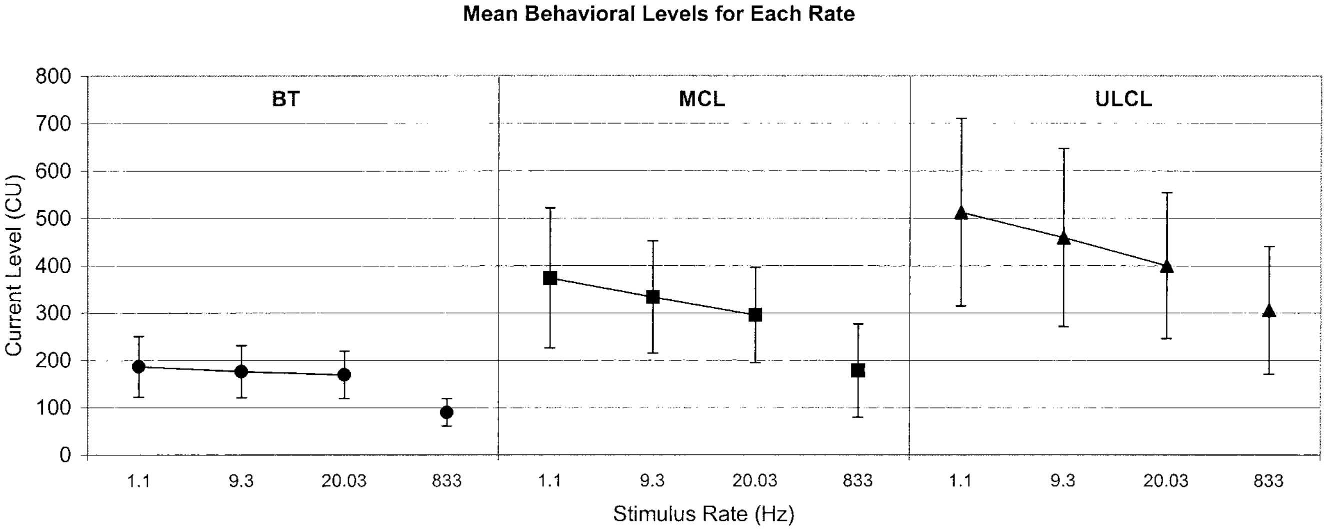

Figure 2. Upper limit of comfort level (ULCL), most comfortable loudness level (MCL), and behavioral threshold (BT) averaged across subjects and Electrodes 1, 4, and 7 for each tested stimulus rate. Symbols represent mean values for BT (circle), MCL (square), and ULCL (triangle) at the stimulus rates of 1.1, 9.3, 20.03, and 833 Hz. CU = clinical units. Error bars represent plus and minus one standard deviation from the mean. All rates had a significant effect on BT, MCL and ULCL ($p \leq 0.05$).

score was calculated by first converting each speech perception score to a standard (z) score. The z scores for each test were averaged to produce a composite score across tests for each subject. Conversion to the standard scores prevents each test score from being automatically weighted in the composite score according to the relative size of the standard deviation of its respective distribution.

The speech perception tests differed in difficulty for these subjects as shown in Figure 1. In quiet, most of the subjects scored higher for the CUNY Q than for the HINT Q, and higher for the HINT Q than for the CNCW. In noise, the majority of subjects scored higher for the CUNY N than for the HINT N, and higher for the HINT N than for the SPIN. Examination of the test scores revealed that each of these speech perception measures (in quiet or noise) tended to identify the subjects with the best and poorest speech perception performance in a similar manner. Subjects 1, 3, and 7 obtained the highest scores for almost all tests. Subjects 4, 8, and 9 obtained little to no open-set word or sentence recognition in either quiet or noise. Subjects 2, 5, 6, 10, and 11 presented scores on almost all of the tests that place them between the best and poorest performers.

Behavioral Measures: Effects of Stimulus Rate and Electrode Site

Figure 2 presents the mean values for BT, MCL, and ULCL for each tested stimulus rate. The fastest rate of 833 Hz resulted in the lowest average BT, MCL, and ULCL, while the highest mean BT, MCL, and ULCL occurred for the slowest rate of 1.1 Hz. Analysis of variance and post hoc comparisons on stimulus rate were significant for all rate comparisons ($p \leq 0.05$) for BT, MCL, and ULCL.

The mean behavioral measures were examined for all subjects and for each electrode site. At each of the stimulus rates, BTs, MCLs, and ULCLs tended to be highest for basal Electrode 7. Although there was an overall significant effect for electrode site for BT, MCL, and ULCL, post hoc comparisons did not show significance for all electrode comparisons. Electrodes 1 and 4 and 1 and 7 were significantly different for MCL and ULCL. Only Electrodes 4 and 7 were significantly different for BT. This suggests that suprathreshold measures of MCL and ULCL were significantly lower at the apical end of the electrode array, but this result did not apply to measures of threshold.

There were significant interactions between stimulus rate and electrode site for the BT and MCL, but not for the ULCL. Post hoc tests for the interaction of the electrode and rate effect for BT were significant for the slower rates (1.1 Hz, 9.3 Hz) but not for the faster rates (20.03 Hz, 833 Hz) for almost all electrodes. For MCL, the majority of electrode and rate effect comparisons were significant, except a few instances in which the electrode effect was not significant at the fastest stimulus rate (833 Hz).

Figure 3 shows the BT, MCL, and ULCL for two subjects obtained at 1.1 Hz, 9.3 Hz, 20.03 Hz, and 833 Hz on each electrode. Subject 9 had no open-set speech perception whereas Subject 10 was able to perceive words and sentences with audition alone.

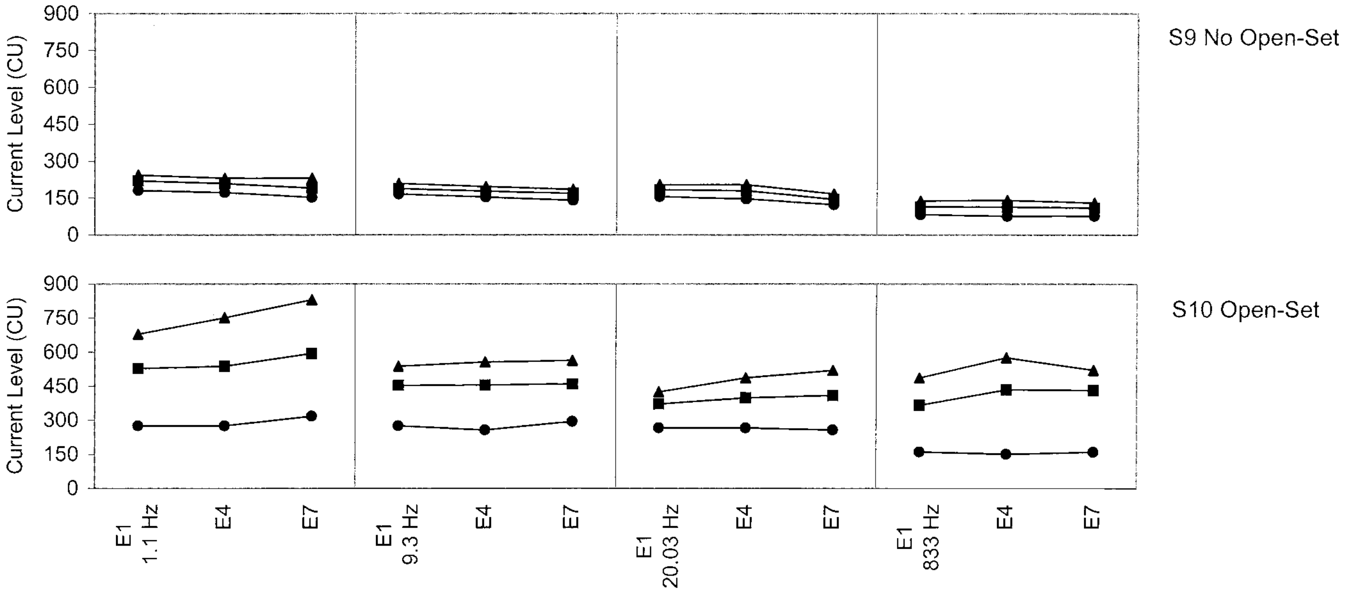

Figure 3. Individual plots for Subject 9 (no open-set speech perception) and Subject 10 (open-set speech perception) show BT (circle), MCL (square), and ULCL (triangle) for each tested stimulus rate and each tested electrode (E1 = Electrode 1, E4 = Electrode 4, E7 = Electrode 7).

For Subject 10 and the majority of subjects, the BT, MCL, and ULCL obtained at 833 Hz were lower than those measured at the slower stimulus rates. As seen in Figure 3, measures of BT, MCL, and ULCL are uniform for Subject 9, resulting in a compressed BDR that changed little with change in stimulus rate. Subjects 4 and 8 also exhibited reduced dynamic ranges. All subjects did not have the same changes in BT, MCL, and ULCL as stimulus rate was changed. The varied effect of stimulus rate on BT, MCL, and ULCL may reflect differences in temporal integration abilities among subjects.

Evoked Potentials

EABR • The morphology of the EABR recordings was consistent with other reported EABR findings (Brown et al., 1990, 1994; Mason et al., 1993; Shallop et al., 1990). The responses were also similar in morphology to acoustically evoked auditory brainstem responses (Jewett & Williston, 1971; Picton et al., 1974). Figure 4 shows individual waveforms recorded for all 11 subjects, ordered by subject number. Repeatable EABR waveforms were recorded from nine subjects on Electrode 1 at the stimulus level corresponding to 100% of the BDR, which is noted to the right of each set of waveforms. Subjects 2, 5, and 6 had the largest Wave V amplitudes (note the change in the μV/division scale denoted by the number of asterisks). Subjects 4 and 9 had no measurable EABRs on any of the three electrodes at any stimulus presentation level. For the remaining subjects, responses contained one to three identifiable positive peaks labeled Waves II, III, and V.

At the maximum stimulus level (100%), Subject 6 generated a Wave V amplitude that was substantially larger than that of the other subjects (note the waveforms are scaled at 6.10 μV/division). This subject also had an unusually large amplitude on Electrode 4 at 100% of the BDR. At all other stimulus levels, Wave V amplitude for Subject 6 fell within the range of the other subjects for each of the three tested electrodes. Because of concern about possible response contamination (due to facial nerve or muscle activation) at the highest stimulus level, the response at 100% for Subject 6 on Electrodes 1 and 4 was not used in subsequent analyses.

EAMLR • The morphology of the Na-Pa response of the EAMLR was generally consistent across subjects and across electrodes, and similar to those reported in other studies (Gardi, 1985; Jyung et al., 1989; Kileny & Kemink, 1987; Kileny et al., 1989; Miyamoto, 1986). The recordings resemble acoustically evoked middle latency responses (Davis, 1976; Özdamar & Kraus, 1983; Picton et al., 1974). Figure 5 shows individual recordings for all 11 subjects on Electrode 1 at 100% of the BDR. EAMLR responses were recorded on at least two electrodes from 8 of 11 subjects. Subjects 4, 8, and 9 had no measurable EAMLRs on any of the three tested electrodes at any stimulus presentation level. One subject, 10, had responses for Electrodes 1 and 4, but not for Electrode 7.

N1-P2 of the ELAR • The morphology of the N1-P2 complex was similar to that reported by other stud-

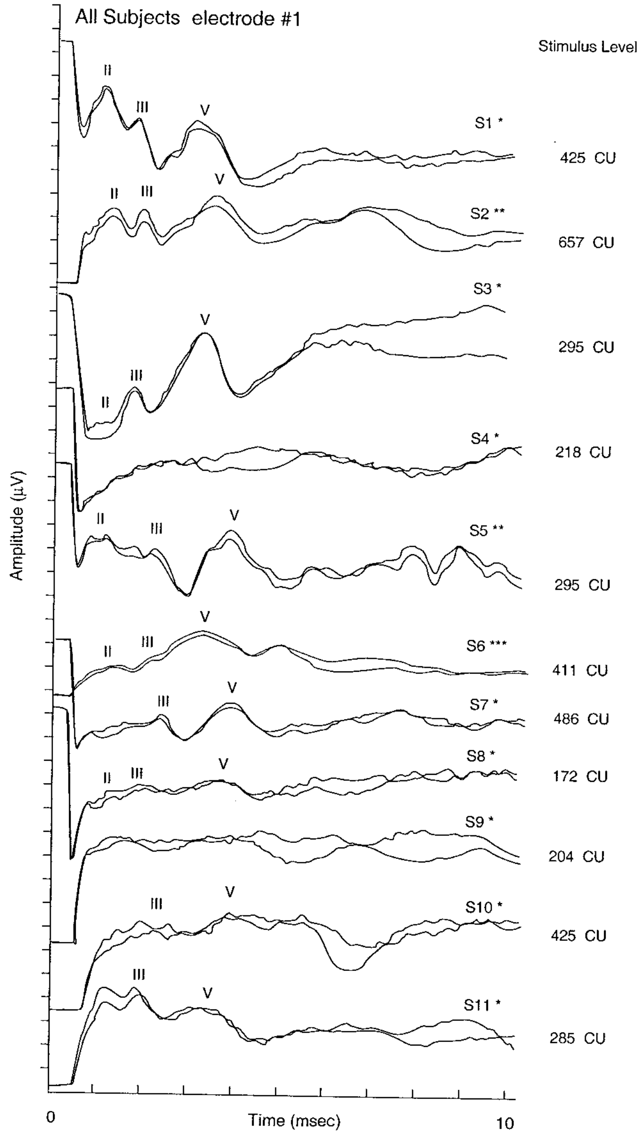

Figure 4. Replicated EABR recordings for all 11 subjects on Electrode 1 at the stimulus level that represented 100% of the subjects' BDR, which is also displayed to the right of each set of waveforms in clinical units (CU). The asterisk(s) next to each subject number denote amplitude in microvolts per division on the y-axis. *0.76 μV/division, **1.52 μV/division, ***6.10 μV/division.

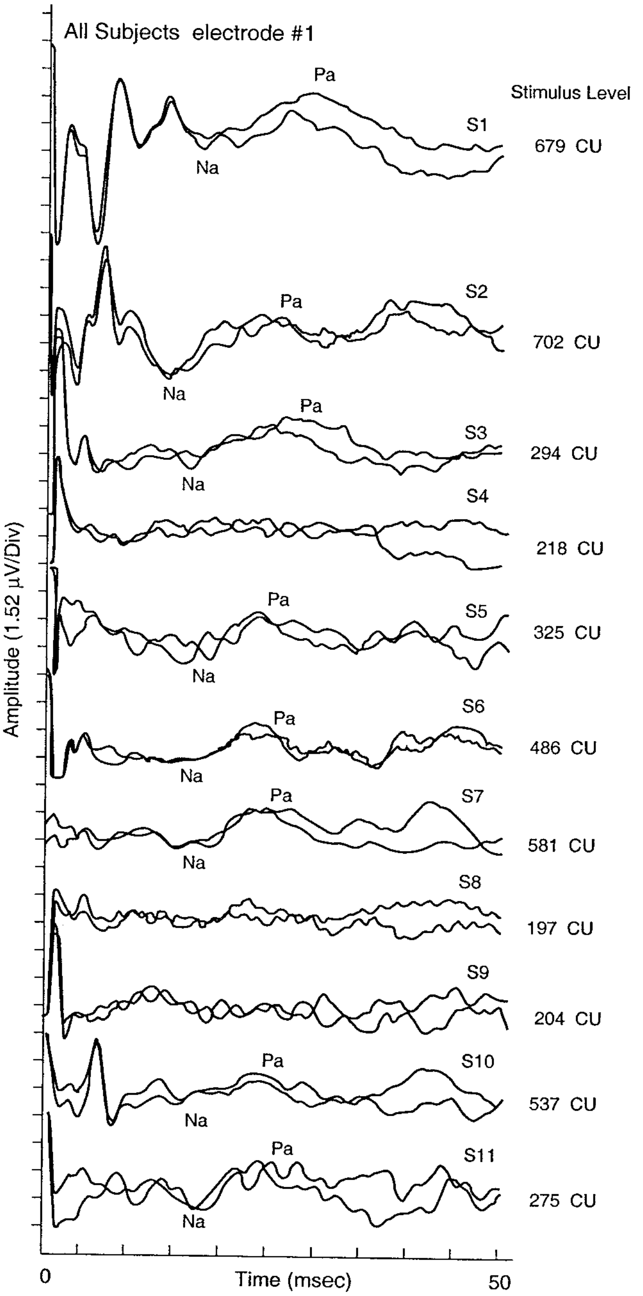

Figure 5. Replicated EAMLR (Na-Pa) recordings for all 11 subjects on Electrode 1 at the stimulus level that represented 100% of the subjects' BDR, which is also displayed to the right of each set of waveforms in clinical units (CU). All waveform amplitudes are plotted at 1.52 μV/division.

ies where recordings have been obtained with cochlear implant subjects (Kraus et al., 1993b; Ponton & Don, 1995) and to acoustically evoked N1 and P2 recordings (Näätänen & Picton, 1987; Picton et al., 1974). Figure 6 shows individual recordings for all 11 subjects on Electrode 1 at the stimulus level equal to 100% of the BDR. The N1-P2 response was recorded for at least two electrodes from 9 of 11 subjects. As with the EABR and EAMLR, Subjects 4 and 9 had no measurable responses on any of the three tested electrodes at any stimulus presentation level. Subject 8, who had no EAMLRs for any electrode or stimulus level, had measurable N1-P2 responses for Electrode 1 only. Subject 10 showed the same pattern of presence and absence across electrodes as for the EAMLR, i.e., Subject 10 had N1-P2 responses for Electrodes 1 and 4, but no responses for Electrode 7. (See Firszt et al. [2002], in this issue for details of the EABR, EAMLR, and ELAR morphology, latency, amplitude, and threshold with

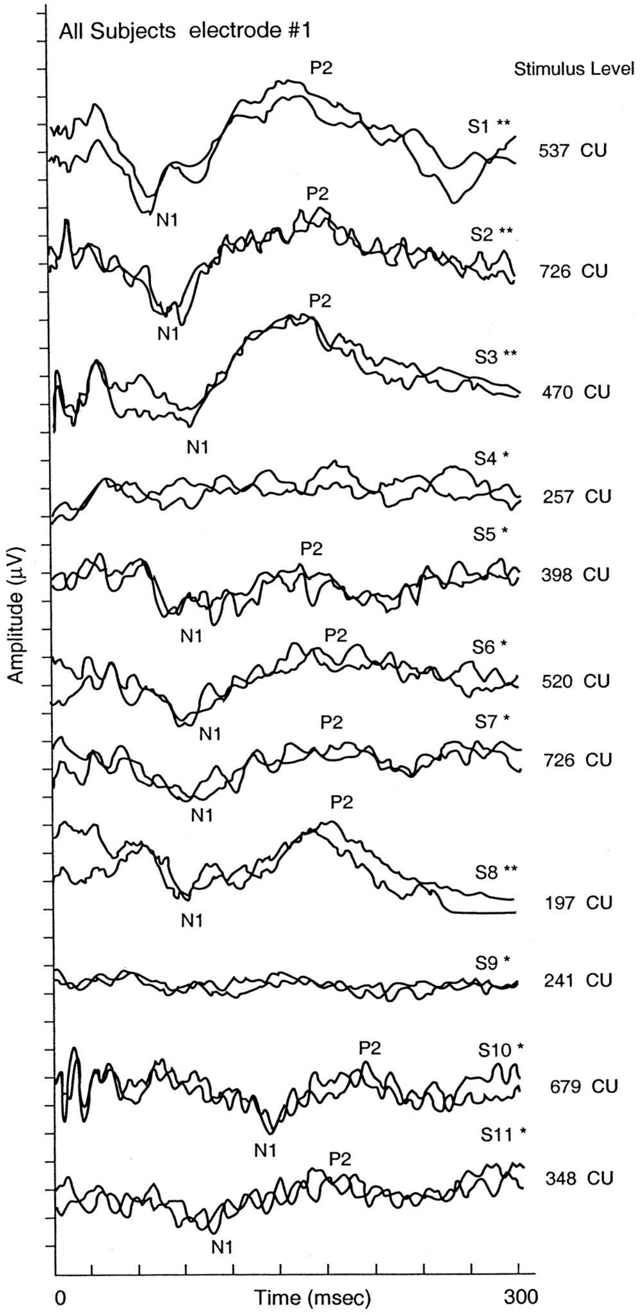

Figure 6. ELAR (N1-P2) recordings for all 11 subjects on Electrode 1 at the stimulus levels that represented 100% of the subjects' BDR. Two replications for each N1-P2 response are displayed for each subject. The asterisk(s) next to each subject number denote amplitude in microvolts per division on the y-axis. *1.52 μV/division, **3.05 μV/division.

respect to implanted electrode location and stimulus level for this subject sample.)

Speech Perception/Evoked Potential Comparisons

Evoked potential and behavioral measures were compared with mean or composite speech perception scores computed for each subject as described previously. Pearson correlation coefficient (r) determined whether a relationship existed between evoked potential and behavioral measures of speech perception using data for the eight subjects who produced all of the evoked potentials, i.e., the EABR, EAMLR, and ELAR. Because all subjects produced behavioral responses (BT, MCL, ULCL) at each tested rate, computation of correlations relating behavioral measures to speech recognition scores involved data from all 11 subjects.

Comparison of Speech Perception Abilities and Evoked Potential Amplitude and Latency

Maximum Amplitude and Normalized Amplitude • Two measures of evoked response amplitude were obtained for each subject, a maximum and normalized amplitude. The maximum amplitude was defined as the largest amplitude on each electrode for each evoked potential (Wave V of the EABR, the Na-Pa complex of the EAMLR, and the N1-P2 complex of the ELAR). The maximum values for each evoked response were averaged across electrodes for each subject, and the average was compared with speech perception scores.

Maximum amplitude measures can be more variable due to the nature of far-field recordings and subject differences (e.g., head size and distance between surface recording electrodes). For this reason, a normalized amplitude was calculated for each electrode by dividing the amplitude value obtained at 100%, 75%, 50% and 25% of the BDR by the maximum amplitude at 100% of the BDR. This computation provided a dynamic measure of how amplitude was maintained across stimulus current levels for a given subject, rather than a static measure of maximum amplitude obtained at one stimulus level. The normalized amplitude measures were averaged across Electrodes 1, 4, and 7 for each subject for Wave V, the Na-Pa complex, and the N1-P2 complex, and compared with composite speech perception scores.

The correlations relating the maximum and normalized amplitudes for each evoked response and the subjects' composite scores for speech perception in quiet and speech perception in noise are displayed in Table 1. There was no relationship between speech perception abilities and maximum amplitude measures for the EABR, EAMLR or ELAR. Of the normalized amplitudes, only the relationship between speech perception scores in quiet and the EAMLR were statistically significant ($p \leq 0.05$), which is further illustrated in Figure 7 (left panel). Subjects 4, 8, and 9 are plotted, for illustrative purposes, with open circles that intersect their re-

TABLE 1. Correlation between composite speech perception scores and evoked potential measures

		Maximum Amplitude			Normalized Amplitude		
Composite Score		EABR	EAMLR	ELAR	EABR	EAMLR	ELAR
Speech in quiet	r	0.08	−0.01	0.23	0.30	0.75*	0.06
Speech in noise	r	0.10	0.01	0.19	0.40	0.65	0.01

		Evoked Potential Threshold in Clinical Units			Evoked Potential Threshold as Percent of BDR		
		WV	Na-Pa	N1-P2	WV	Na-Pa	N1-P2
Speech in quiet	r	−0.41	−0.69*	−0.17	−0.21	−0.74*	−0.10
Speech in noise	r	−0.38	−0.65	−0.12	−0.23	−0.77*	−0.08

r = Pearson correlation.

* $p \leq 0.05$.

Speech in quiet = average z score for CNC, CUNYQ, HINTQ; Speech in noise = average z score for CUNYN, HINTN, SPIN-R.

spective speech perception score and assigned amplitude of zero. Recall that the correlational analyses included only those subjects for whom electrophysiologic responses could be recorded.

Absolute Latency • The absolute latencies of the evoked potentials at 100% of BDR, 75% of BDR and EPT were compared with the speech perception scores for the subjects who produced all evoked potentials. For this data set, none of the comparisons showed statistical significance.

Comparison of Speech Perception Abilities and Evoked Potential Thresholds

The thresholds of Wave V, the Na-Pa complex (Na-PaT), and the N1-P2 complex (N1-P2T) were compared with speech perception performance in two ways. For one comparison, the EPT was expressed in CU and averaged across the electrodes for each subject. For the second comparison, the EPT on each electrode was expressed as the percentage of the BDR at which the threshold occurred. The percentages were then averaged across electrodes for each subject. In Table 1, the pattern of correlations across the evoked potentials again favors the EAMLR. The r for the Na-Pa threshold expressed in CU for speech in quiet was statistically significant ($p \leq 0.05$), as were the r's for the Na-Pa threshold expressed as a percentage of the BDR for both speech in quiet and noise. Figure 7 displays the scatterplots for the correlations between Na-Pa threshold and speech perception scores in quiet expressed in CU (middle panel) and as a percentage of the BDR (right panel). The data suggest that higher speech perception scores occurred for the subjects with lower Na-Pa thresholds.

Comparison of Speech Perception Abilities and BT, MCL, ULCL, and BDR

For each subject, the mean BT, MCL, and ULCL obtained at the stimulus rate of 833 Hz were computed by averaging across electrodes. The correlations obtained from comparison of these values to the composite speech perception scores in quiet and in noise for all 11 subjects are shown in Table 2.

TABLE 2. Correlation between composite speech perception scores and behavioral measures

		Behavioral Measures in Clinical Units			
Composite Score		BT	MCL	ULCL	BDR
Speech in quiet	r	0.03	0.56	0.68*	0.75*
Speech in noise	r	−0.10	0.49	0.62*	0.71*

		Derived Differences in Clinical Units		
Composite Score		BTDIF	ULCLDIF	BDRDIF
Speech in quiet	r	0.24	0.63*	0.69*
Speech in noise	r	0.34	0.62*	0.70*

r = Pearson correlation.

* $p \leq 0.05$.

BT, MCL, and ULCL are obtained at a stimulus repetition rate of 833 Hz.

BTDIF = difference in behavioral threshold obtained at stimulus rates of 833 Hz and 1.1 Hz; ULCLDIF = difference in upper limit of comfort level obtained at stimulus rates of 833 Hz and 1.1 Hz; BDRDIF = difference in behavioral dynamic range obtained at stimulus rates of 833 Hz and 1.1 Hz; Speech in quiet = average z score for CNC, CUNYQ, HINTQ; Speech in noise = average z score for CUNYN, HINTN, SPIN-R.

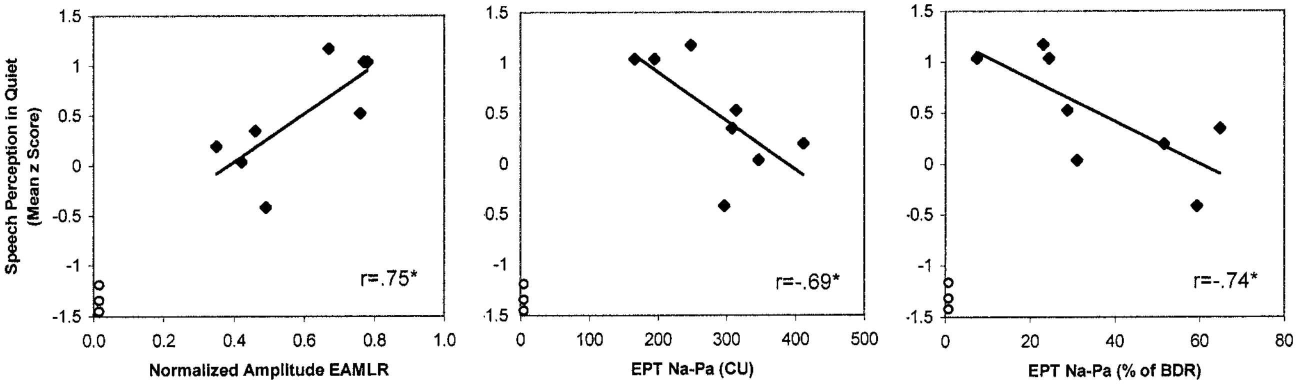

Figure 7. Scatterplots show the relation between speech perception scores and measures of the EAMLR for all subjects for whom responses were obtained. Speech in quiet represents average z score for CNC, CUNY Q, and HINT Q. The panels show speech perception in quiet compared with a) normalized amplitude (left panel), b) Na-Pa threshold in clinical units (middle panel), and c) Na-Pa threshold expressed as a percentage of the subject's behavioral dynamic range. Open circles represent three subjects with no EAMLR and no open-set speech perception, although their data are not included in the correlational analyses.

There was no significant relation between the BT or MCL and speech perception scores. The correlations were significant, however, between ULCL and speech in quiet and speech in noise, as well as for BDR and these speech measures ($p \leq 0.05$). Figure 8 displays these relations as scatterplots in the upper and lower panels labeled A and B.

To examine the BDR across stimulus rates for individual subjects, a BDR difference score was calculated for each subject by subtracting the BDR averaged across electrodes at the fastest stimulus rate (833 Hz) from the BDR averaged across electrodes at the slowest stimulus rate (1.1 Hz). This same computation was completed for the measures of BT and ULCL and the correlations resulting from the comparison with composite speech recognition scores in quiet and in noise for all 11 subjects are shown in Table 2. The difference in the ULCL and BDR between the fastest and slowest stimulus rates were statistically significant for speech in quiet and in noise ($p \leq 0.05$). Figure 8 displays these relations as scatterplots in panels C and D. These findings suggest that the subjects who demonstrated more change in ULCL and in BDR with decrease in

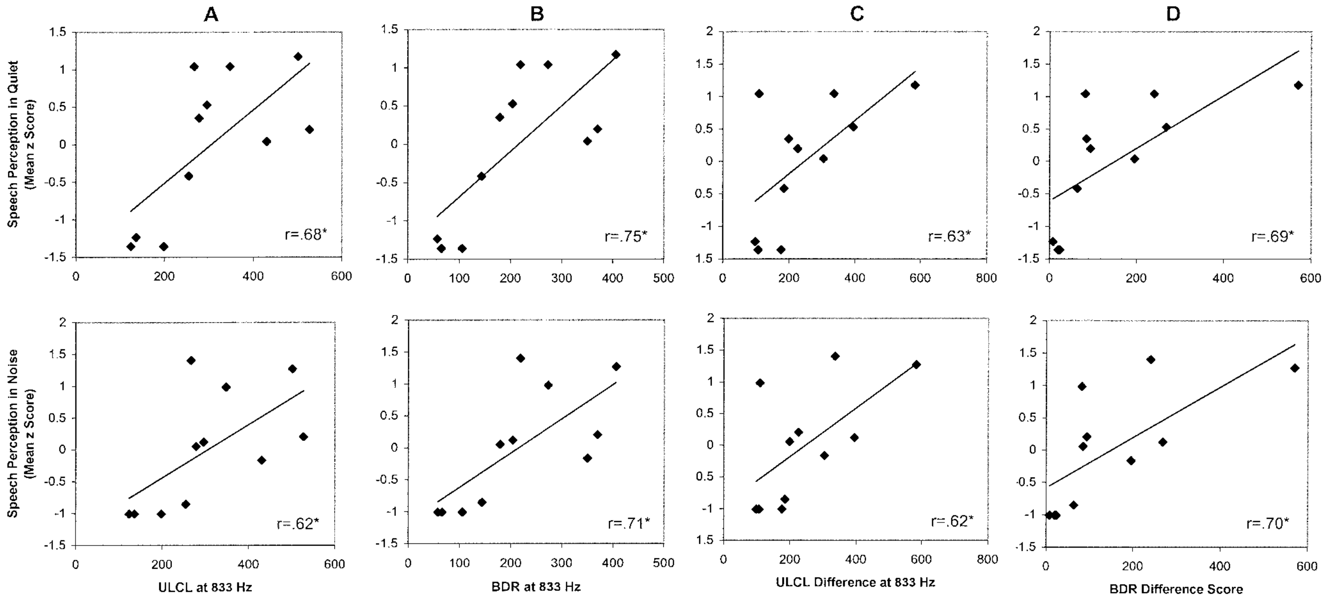

Figure 8. Scatterplots show the relation between speech perception scores and measures of ULCL and BDR for all subjects. Speech in quiet (upper panels) represents average z score for CNC, CUNY Q, and HINT Q. Speech in noise (lower panels) represents average z score for CUNY N, HINT N, and SPIN-R. Values for ULCL and BDR were averaged across electrodes. The panels show speech perception in quiet or noise compared with A) ULCL at 833 Hz, B) BDR at 833 Hz, C) the difference in ULCL at 833 Hz versus 1.1 Hz, and D) the difference in BDR at 833 Hz versus 1.1 Hz.

stimulus rate tended to have better speech perception scores. Changes in the BDR may relate to changes in either BT or ULCL because both measures define the BDR. Examination of the differences in BT and ULCL at the rates of 833 Hz and 1.1 Hz indicated that a change in BDR more closely relates to a change in ULCL ($r = 0.969$) rather than a change in BT ($r = 0.557$).

DISCUSSION

Overall, this study compared electrically evoked potentials that reflect different levels of the auditory pathway with behavioral measures to better understand functional outcomes of subjects who use cochlear implants.

Speech Perception Data

Of the speech perception measures administered, the CUNY Q, CUNY N, and HINT Q had the highest scores averaged across subjects. The HINT N and CNCW were the next most difficult, followed by the SPIN-R test. For all of the subjects who had some open-set speech recognition, there was a substantial decrease in performance for the test items on the SPIN-R test. It was of interest that the three subjects with the best speech perception scores each commented that the difficulty in word recognition in the presence of background noise on the SPIN-R test was similar to their perception of the communication difficulties they encounter on a daily basis. High monosyllabic word and sentence recognition scores obtained in a quiet sound-treated booth under ideal listening circumstances at 70 dB SPL does not reflect the communication demands that cochlear implant users confront on a daily basis.

Behavioral Data

The lowest values of BT, MCL, and ULCL were obtained with the fastest stimulus rate of 833 Hz, and the highest values were obtained with the slowest stimulus rate of 1.1 Hz. This finding is consistent with other psychophysical experiments with cochlear implant users and pulsatile stimuli in which thresholds were higher for low stimulus repetition rates than for high stimulus repetition rates (Eddington, Dobelle, Brackmann, Mladejousky, & Parkin, 1978; Pfingst, 1984; Shannon, 1985; Tong, Clark, Blamey, Busby, & Dowell, 1982). The result that BT did not show a relationship with speech perception scores agrees with other reports (Dankowski, McCandless, & Dorman, Reference Note 2).

The poorest speech perception performers among the subjects in the present study had the smallest BDR and the smallest BDR difference scores. These measures of the BDR did not, however, differentiate the better performers, a finding noted by Kessler, Loeb and Barker (1995) and Dorman and Loizou (1998). The data in the present study show that BDR is influenced more by ULCL than it is by BT. The ULCL, the upper limit of the BDR, has been proposed to vary depending on the stimulated electrode, the electrode spacing, and nerve survival (Pfingst, 1984). The upper measure of the BDR is defined by the subject's perception of loudness. In the present study, it may be that subjects with very reduced BDRs have abnormal loudness growth functions that result from impairment in the peripheral and/or the central auditory system.

Comparisons of Evoked Potentials and Speech Perception Data

The parameters of the EABR (e.g., latency, maximum amplitude, normalized amplitude, and threshold of Wave V) were not strongly associated with speech perception performance in this study for the eight subjects who produced all of the evoked responses. Weak or absent correlations between speech perception and EABR measures of threshold, latency and amplitude have been reported in the literature (Brown et al., 1995). Early studies in the '70s and '80s that investigated the EABR were focused on the relation between the amplitude of the Wave V response and spiral ganglion cell count, assuming that the population of surviving neurons is related to the health of the auditory system and ultimately related to speech perception abilities. Although some studies concluded that a relation existed between the EABR and spiral ganglion cell survival (Lusted, Shelton, & Simmons, 1984; Simmons & Smith, 1983), other studies were not in agreement (Shepherd et al., 1983; Steel & Bock, 1984; van den Honert & Stypulkowski, 1986). Perhaps spiral ganglion cell and/or auditory nerve survival is not as directly related to the performance of implant users as once believed, or on the other hand, perhaps neural survival does relate but the measures of the EABR are not successful in resolving the association.

Most studies of the EAMLR have focused on the ability to generate adequate stimulation of the central auditory system or to predict behavioral measures related to those used for programming, rather than examination of the relation of the EAMLR to speech perception performance. In the present sample of subjects, there was a trend for greater EAMLR normalized amplitude measures and lower thresholds for the Na-Pa complex to be associated with higher speech perception abilities. A relation between EAMLR inter-electrode variability and speech perception scores of Nucleus users has been reported (Groenen, Snik, & van den Broek, 1997). Auditory abilities may be reflected in the EAMLR of cochlear implant users because the Na-Pa response represents activity in the thalamus and primary auditory cortex.

For the eight subjects who produced all of the evoked responses, the parameters of the N1-P2 response of the ELAR (e.g., latency, maximum amplitude, normalized amplitude, and threshold of the N1-P2 complex) were not strongly associated with speech perception abilities. Traditionally N1 is thought to indicate conscious detection of an auditory stimulus, rather than discrimination of stimuli (Näätänen, 1990). In a study with normal-hearing subjects (Whiting, Martin, & Stapells, 1998), N1 remained identifiable even when N2 and P3 were absent and when the subject could not discriminate the stimuli in the behavioral task. With a repetitive nonspeech stimulus, as employed in this study, the presence of the N1 and P2 components may provide information about the integrity of the system to detect electrical stimuli, but may not be associated with word or sentence recognition ability.

On the other hand, it is likely that relations exist between how sounds are represented in the central auditory system and behavioral perception measures. Studies have shown that the N1-P2 and MMN components reflect changes in neural activity that occurs as a result of stimulation or deprivation. For example, the amplitude of the N1-P2 and MMN response has been shown to increase after speech sound training in normal-hearing listeners (Kraus, McGee, Carrell, King, Tremblay, & Nicol, 1995; Tremblay, Kraus, & McGee, 1998; Tremblay et al., 2001). P1-N1 amplitude has been shown to increase in the ipsilateral ear of subjects with unilateral hearing loss compared with greater contralateral activation in normal-hearing subjects (Ponton, Vasama, Tremblay, Khosla, Kwong, & Don, 2001). These findings suggest that representation at the central auditory level can be changed and these changes can be reflected in the N1-P2 response. Much work remains to understand the neurophysiologic link between central auditory mechanisms and the perception of words, which requires higher-level linguistic abilities.

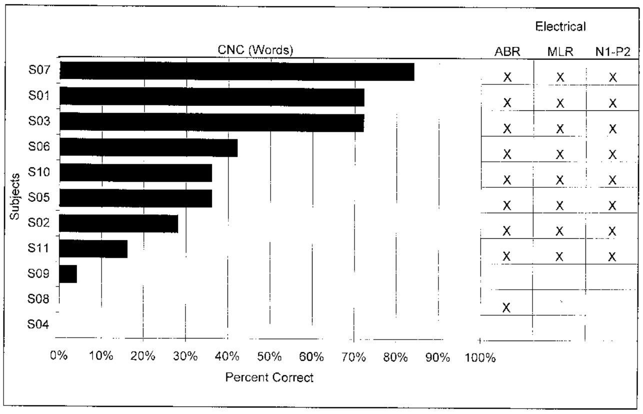

Figure 9. Percentage of correct CNC word scores for each subject ranked from highest to lowest. An X in the respective column designates the presence of the electrical ABR, M. L. R., and N1-P2 on at least two of three electrodes for individual subjects.

Current Study Findings

Unique aspects of the present study included the combination of evoked potential recordings obtained for the EABR, the EAMLR, and the ELAR within the same subject to evaluate the integrity of the auditory pathway with an electrophysiologic measure specific to the level being assessed. Figure 9 summarizes the presence of physiologic responses on at least two of three tested electrodes and CNC words correct for studied subjects. The presence of responses at all three levels of the auditory pathway was associated with at least some open-set speech perception performance and suggests generally intact neural integrity from the peripheral to the central system. Also unique to this study was the systematic collection of evoked responses that sampled the BDR from a minimum level of BT to a maximum level of the ULCL. In most previous studies, electric evoked potentials were obtained at one stimulus level only. Because the current study included recordings from across the BDR, it was possible to evaluate the responsiveness of the system at lower stimulus levels. The normalization of the amplitude measures provided a dynamic measure of how amplitude is maintained across stimulus current levels, rather than a static measure of maximum amplitude at one stimulus level. Of the evoked potentials studied in this subject sample, the electric middle latency response was most closely associated with better speech perception performance. Further study is needed to determine whether this association would hold true for a larger sample size and for speech-like stimuli. If so, it may suggest that the midbrain and the higher levels of the central system particularly reflect the coding of speech with electrical stimulation.

Variables That Profile Better and Poorer Performers for Speech Perception

In this data set, the presence of electrically evoked potentials at all three levels of the auditory pathway was a common factor for those subjects with better speech perception scores. Subjects 1, 3, and 7 had identifiable responses for EABR, EAMLR, and ELAR on all three tested electrodes, although they did not always have the same characteristics. There was no systematic relationship between maximum response amplitude and any of the evoked potential measures. That is, although the presence/absence of waveforms was related to speech perception, better performers were not necessarily those with the largest maximum amplitudes.

In this sample of subjects, the three poorest speech perception performers had scores of 0% to 10% collectively on any speech recognition measure. Two subjects had no identifiable evoked potential responses for the EABR, EAMLR or ELAR. One subject had identifiable EABRs on the three tested electrodes, with rather poor morphology and the smallest Wave V amplitude of the measured responses. EAMLRs could not be recorded for this subject, and ELAR responses were obtained on Electrode 1 only. The three subjects with the poorest speech perception scores had the smallest BDR for each of the tested stimulus rates compared with the remaining subjects. These subjects also had the smallest change in BDR with a change in stimulus rate from 1.1 to 833 Hz, and the lowest ULCLs. Sensitivity to temporal differences is critical for speech understanding (Phillips, 1993; Phillips & Hall, 1990). Diminished performance with increased stimulus rates has been documented in individuals with learning problems and/or poor speech understanding (Kraus, McGee, Carrell, Zecker, Nicol, & Koch, 1996; Tallal & Piercy, 1974).

With respect to the EPT of the response, the better performers for speech perception did not have the lowest thresholds for the EABR or the ELAR. The lowest Na-Pa thresholds of the EAMLR in this sample of subjects expressed either in CU or as a percentage of the BDR were recorded from the three best performers. The remaining variables related to the evoked potentials (e.g., absolute latency of response, amplitude-intensity functions) did not effectively distinguish those subjects with better and poorer speech perception scores nor did the behavioral measures of BT and MCL.

Of the demographic variables that describe the background characteristics of the subjects, the best performers had periods of auditory deprivation (time period between onset of bilateral profound hearing loss and age at implantation) of 1 to 2 yr. Poorer performers had the longest periods of auditory deprivation (e.g., 24 yr for Subject 4 and 14 yr for Subject 9). Subject 8 had asymmetric hearing levels that were mild in the left ear and severe in the right ear beginning at age 3 yr. Profound hearing levels were documented by 12 yr of age bilaterally. Based on the age of implantation, the period of auditory deprivation was 12 yr for the left ear and 21 yr of severe-to-profound hearing loss for the right ear, the ear chosen for implantation.

Subjects 4, 8, and 9 are considered postlinguistically deafened. Subject 4 had onset of moderate hearing loss at age 18 yr that did not become profound until age 40. As mentioned, Subject 9 had moderate hearing loss in her 40s that progressed to profound at age 64 yr. The poor performance and lack of/or poor physiologic responses at levels of the auditory pathway for these subjects suggests that there may be a critical time window for successful cochlear implantation even for individuals with postlinguistic hearing loss. Subject 8 met the criteria for postlinguistic deafness, defined as profound hearing loss onset after the development of spoken language, generally by age 7 yr. This case suggests that performance is influenced by the variation in age at onset of hearing loss (particularly during early childhood), by the degree and progression of hearing loss (from onset to profound) for each over time, and by the length of auditory deprivation (from profound to implantation) for each ear.

Subject 11 was the fourth poorest performer among this sample of subjects, but did have the least amount of cochlear implant use, that of 3 mo (the minimum length of use for inclusion in the study). The hearing loss history is of particular interest for Subject 11. Contraction of mumps at the age of 7 yr resulted in profound hearing loss in the left ear. Because the right ear was unaffected, amplification was not used. This subject had normal hearing in the right ear until age 46 yr when she was diagnosed with a hemangioma of the internal auditory artery and lost all hearing at the time of tumor removal. Subject 11 received a cochlear implant 1 mo later in the left ear, which had been deafened for 40 yr. Although the speech perception scores for Subject 11 were in the lower range for this sample of subjects, it is remarkable that at 3 mo postactivation, scores of 58% (CUNY Q), 40% (HINT Q), 16% (CNCW), and 20% (CUNY N) were obtained. It is also of interest that Subject 11 had some open-set speech recognition, and the presence of evoked potentials (EABR, EAMLR, and ELAR) on all tested electrodes at 3 mo after implantation when electrically stimulated in an ear that had not received direct peripheral input for 40 yr. The fact that hearing was normal in the contralateral ear for 47 yr suggests that outcomes for subjects with cochlear implants depends not only on the history of hearing in the implanted ear, but the contribution of the nonimplanted ear over time as well.

In summary, a combination of variables tended to distinguish the poorer subjects with little to no speech recognition on any of the tests from the remaining subjects in this data set. These variables included 1) poorly formed or absent evoked potential responses, 2) reduced BDRs, 3) lack of change in the size of the BDR with a change in the stimulus rate, and 4) longer periods of auditory deprivation. The variables that tended to differentiate the best performers from the other subjects in this data set included 1) presence of responses at all three levels of the auditory pathway, with large normalized amplitudes for the electric auditory middle latency response, 2) lower EPTs for the Na-Pa complex, 3) relatively large BDRs, and 4) relatively large changes in the size of the BDR with a change in the stimulus rate.

When speech is processed through a cochlear implant, different parts of the peripheral and central pathways are engaged depending on the stimulus. Speech perception is reflected in auditory pathway physiology. Measures such as evoked potentials, which are inherently dependent on neural synchrony, allow us to evaluate the critical synchronous components of neural encoding. The study findings illustrate that variability in speech perception scores of cochlear implant recipients relates to neurophysiologic responses at thalamo-cortical levels of the auditory pathway. Presumably, limited neural synchrony for elicitation of electrophysiologic responses underlies limited speech perception. In addition, the inability to follow change in the temporal characteristics of the stimulus was associated with poor speech perception performance. Findings confirm that neural encoding with electrical stimulation must provide sufficient physiologic responses of the central nervous system to perceive speech through a cochlear implant.

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