

# Electrode Discrimination and Speech Perception in Young Children Using Cochlear Implants

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**Objective:** The aim was to determine the efficacy of a child-appropriate procedure to assess electrode discrimination ability in young children using cochlear implants and to investigate the relationship of electrode discrimination ability and speech perception performance in children implanted at a young age.

**Design:** An adaptation of the play audiometry procedure was used to assess electrode discrimination in seventeen 4- to 10-yr-old children. The children were required to respond with a game-like motor response when a repeating stimulation on a reference electrode "changed" to a different electrode. They were also assessed on a speech feature discrimination test, a closed-set word recognition test and a nonverbal intelligence task.

**Results:** Sixty-five percent of subjects demonstrated ability to discriminate adjacent electrodes in mid and apical regions of the cochlea, whilst the remaining subjects needed electrode separations of between two and nine electrodes for successful discrimination. In a forward stepwise regression analysis electrode discrimination ability was found to be the strongest factor in accounting for variance in the speech perception scores. Subject variables such as duration of deafness, nonverbal intelligence and implant experience did not significantly account for further variance in the speech perception scores for this group of children.

**Conclusions:** Electrode discrimination ability was the strongest factor in predicting performance on speech perception measures in a group of children using cochlear implants.

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The ability of early-deafened children who use cochlear implants to discriminate and recognize speech sounds varies over a wide range. Many studies have shown that factors such as duration of profound deafness, age at onset of profound loss, and duration of implant use help to predict speech perception performance (Dowell, Blamey, & Clark, 1997; Fryauf-Bertschy, Tyler, Kelsay, Gantz, & Woodworth, 1997; Sarant, Reference Note 1; Staller, Dowell, Beiter, & Brimacombe, 1991). In a mul-

tichannel cochlear implant, spectral information in speech sounds is coded through the stimulation of different electrodes in accordance with the tonotopic organization of the cochlea (McDermott, McKay, & Vandali, 1992; Skinner, et al., 1994). Several studies with adults using cochlear implants, have indicated that the number of perceptually distinct electrodes is an important factor predicting speech perception performance (Collins, Zwolan, & Wakefield, 1997; Henry, McKay, McDermott, & Clark, 1997; Nelson, Van Tasell, Schroder, Soli, & Levine, 1995). There is limited research into the relationship between electrode discrimination and speech perception performance in early-deafened children, however.

Busby, Tong, and Clark (1993) reported that only one of the four early-deafened patients tested showed good electrode discrimination and a gain in speech perception scores with a multielectrode strategy compared with a single-electrode strategy. This child was implanted younger than the other patients, at 5 yr of age. In a later study with six early-deafened patients, Busby and Clark (1996) reported electrode position difference limens of less than two to three electrodes for most patients with the exception of one patient who had a greater duration of profound deafness and was implanted at a later age. Dawson and Clark (1997) found that electrode position difference limens ranged between one and three electrodes for four out of five congenitally deafened subjects whose ages ranged from 8 to 21 yr at the time of testing. One of the oldest subjects in the study had a much poorer difference limen in the apical region, being unable to discriminate electrodes separated by less than five electrodes. In a most recent study by Busby and Clark (2000) with 16 early-deafened patients ranging in age from 8 to 21 yr, average difference limens across three positions on the array were less than two electrodes for 75% of patients. The remaining patients had limens between 2 and 5.3 electrodes. There were significant correlations between closed-set word recognition scores and electrode discrimination ability in the apical region. The latter was not associated with any subject variables such as implant experience.

In the above-mentioned studies with older children and adolescents, stimuli that vary randomly in loudness were chosen to minimize the possibility of

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the patient using loudness cues to discriminate between electrodes. Studies on electrode discrimination in adults typically use a loudness-balancing procedure and consequently use stimuli that do not intentionally vary in loudness (Collins et al., 1997; Nelson et al., 1995; Zwolan, Collins, & Wakefield, 1997). It is difficult to effectively loudness balance electrodes in younger children (Dawson, Nott, Clark, & Cowan, 1998; Poissant, Brackett, & Peters, Reference Note 2). Hence it is important to use level jitter (random variations in loudness) when investigating electrode discrimination in younger children. There is perhaps another important reason for using jitter, indicated by the work of Henry, McKay, McDermott, and Clark (2000), who investigated the ability of 15 adult implantees to discriminate adjacent electrodes in the presence of random loudness variations. Henry argues that such an ability is more akin to real-life situations in which implantees have to perceive place of stimulation information in the presence of random loudness variation when processing speech sounds. When using jitter within the upper 20%, 40% and 60% of the subject's dynamic range, she found that there were significant correlations between the amount of speech information perceived and adjacent electrode discrimination ability for low-mid electrodes corresponding to the frequency region 170 to 2680 Hz. There were no significant correlations between the amount of speech information perceived and adjacent electrode discrimination ability in the no-jitter condition.

There appears to be some consensus in the literature that electrode discrimination ability is a factor that significantly accounts for some of the variance in speech perception ability for postlinguistically deafened adults and for early-deafened older children, teenagers and young adults. It is important to be able to identify electrode discrimination problems in children as early as possible, so that training or strategies that aim to alleviate the problems can be trialed during the critical years of language development. There is no known research that has assessed electrode discrimination in children younger than 8 yr using cochlear implants. Busby and Clark (2000) have used an adaptive three-interval forced choice procedure to assess electrode discrimination ability in early-deafened children and teenagers. This procedure is not conceptually appropriate for young children. The present study uses a modification of play audiometry to enable the assessment of electrode discrimination in young children (Dawson et al., 1998). It will investigate the efficacy of this procedure for assessing electrode discrimination in children as young as 4 yr, using loudness variation within the upper 40% of the children's dynamic ranges. All preschoolers in metropolitan Melbourne

who were available, were assessed in this study. Unfortunately children under 4 yr of age were unavailable for testing, but the procedure under investigation has been used successfully with children as young as 2 yr of age in assessing speech feature discrimination (Dawson et al., 1998).

Electrode discrimination ability and the subject variables; age at implantation and duration of deafness, covaried in the study by Busby and Clark (2000). This covariance made it difficult to clearly determine the unique contribution of electrode discrimination ability in explaining the between subject variability in speech perception performance. The present study selected a group of children whose duration of deafness and age at implantation varies over a much smaller range than that in the Busby and Clark study.

The study was specifically designed to determine:

1. Whether electrode discrimination could be assessed efficiently in younger children using a play audiometry based, child-appropriate procedure.
2. Whether electrode discrimination ability is related to speech perception performance in young children using cochlear implants.
3. Whether subject variables relating to auditory deprivation, auditory experience and nonverbal intelligence account for variance in the psychophysical and speech perception tasks.

## METHODS

### Patients

Seventeen children aged 4 yr 5 mo to 10 yr 8 mo, who use the 22-electrode Cochlear Ltd cochlear implant, took part in the study. All of the children use the Spectra strategy (Skinner et al., 1994) except for Child 15, who uses the Multipeak strategy (Skinner et al., 1991). Table 1 provides a summary of patient details for these subjects. For most children the electrode array was fully inserted into the scala tympani. Some electrodes were deactivated for some children due to partial insertion or unpleasant sensations or an open or short circuit. Child 4 used pseudo-monopolar stimulation in which the current flowed from the active electrode to a basal electrode, which was shorted to a stiffening ring in the middle ear. The common ground mode of stimulation was used for the majority of children. In this mode the current flows from a single active electrode to all remaining electrodes. Bipolar stimulation was used for the remaining children. For four children the two electrodes in the bipolar pair were separated by one electrode (BP+1). The electrodes in each pair were separated by two electrodes for Child 9 and by four electrodes for Child 12 to ensure that comfortable listening levels were within the implant's operating

TABLE 1. Patient details.

Patient	Onset of Loss	Aetiology	Mode of Communication	Duration of Profound Deafness	Age at Implantation	Age at Time of Testing	Number of Electrode Channels	Mode of Stimulation	Duration of Implant Use
1	Congenital	Unknown	Auditory/oral	1 yr 10 mo	1 yr 10 mo	6 yr 2 mo	20	CG	4 yr 4 mo
2	Congenital	Unknown	Auditory/oral	4 yr 9 mo	4 yr 9 mo	6 yr 2 mo	20	CG	1 yr 5 mo
3	Congenital	Unknown	Total communication	2 yr 11 mo	2 yr 11 mo	6 yr 4 mo	20	CG	3 yr 5 mo
4	Congenital	Charge association	Total communication	2 yr 4 mo	2 yr 4 mo	5 yr 8 mo	17	Monopolar	3 yr 4 mo
5	Congenital	Unknown	Total communication	5 yr 7 mo	5 yr 7 mo	7 yr 3 mo	18	CG	1 yr 8 mo
6	Congenital	Unknown	Auditory/oral	2 yr 11 mo	2 yr 11 mo	6 yr 11 mo	14	BP + 1	4 yr
7	10 mo	Meningitis	Auditory/oral	4 yr 10 mo	5 yr 8 mo	7 yr 9 mo	20	CG	2 yr 1 mo
8	Congenital	Rubella	Auditory/oral	2 yr 2 mo	2 yr 2 mo	9 yr 2 mo	20	CG	7 yr
9	10 mo	Meningitis	Auditory/oral	2 yr 4 mo	3 yr 2 mo	9 yr 1 mo	14	BP + 2	5 yr 11 mo
10	Congenital	Unknown	Auditory/oral	3 yr 3 mo	3 yr 3 mo	9 yr 9 mo	16	BP + 1	6 yr 6 mo
11	2 yr 3 mo	Mastoidectomies	Total communication	3 yr 2 mo	5 yr 5 mo	9 yr 1 mo	20	BP + 1	3 yr 6 mo
12	1 yr 2 mo	Meningitis	Total communication	2 yr 4 mo	3 yr 5 mo	10 yr 8 mo	13	BP + 4	7 yr 3 mo
13	Congenital	Waardenberg syndrome	Total communication	2 yr 6 mo	2 yr 6 mo	4 yr 5 mo	20	CG	1 yr 11 mo
14	Congenital	Familial	Total communication	2 yr 3 mo	2 yr 3 mo	5 yr	20	CG	2 yr 9 mo
15	Congenital	Unknown	Total communication	4 yr 4 mo	4 yr 4 mo	10 yr 2 mo	22	CG	5 yr 10 mo
16	Congenital	Waardenberg syndrome	Total communication	6 yr 7 mo	6 yr 7 mo	10 yr 7 mo	20	BP + 1	4 yr
17	1 yr 1 mo	Meningitis	Total communication	8 mo	1 yr 9 mo	7 yr 6 mo	19	CG	5 yr 9 mo
Mean	4 mo			3 yr 3 mo	3 yr 7 mo	7 yr 9 mo			4 yr 2 mo

range. Electrode 13 had a BP+3 mode of stimulation for Child 12.

**Equipment**

All assessments were conducted using portable equipment in a quiet room in the school settings. A portable computer (AcerNote 950) with a 16-bit built-in sound card was used to administer computer programs designed to administer the Speech Feature Test (SFT) (Dawson et al., 1998) and electrode discrimination task. Speech stimuli were presented via a self-amplified portable speaker (BOSE Lifestyle Powered System) with a broad frequency response (80 Hz to 15 kHz). The speaker was mounted on a tripod positioned 1 meter from the child's ear and the sound level at the ear was calibrated using a sound level meter to 68 dBA.

**Assessment**

**Loudness Comfort Levels** • In the initial assessment the maximum comfortable levels (C levels) for each electrode for each child were adjusted. The thresholds (T levels) and maximum comfortable levels for each electrode are expressed as clinically used stimulus level steps. The stimulus level scale codes amplitude. In this scale the current amplitude is constant at 1000  $\mu$ A over most of the stimulus level range (65 to 229 levels), whilst the pulse width alters exponentially and is associated with a rise in perceived loudness. The pulse width is constant and the current amplitude rises exponentially in the upper and lower parts of the stimulus level scale (Skinner et al., 1991).

The C levels obtained in the initial assessment were used as the stimulation levels on the reference and comparison electrodes in the psychophysical testing. They were measured using an ascending-descending technique. The stimulus level was increased until the child reported the stimulation to be too loud and then decreased until it was tolerably loud. The younger children were encouraged to give a verbal response such as "ssh" or a nonverbal gesture to "turn the sound down." Whenever possible the children were encouraged to sit next to the audiologist and push the spacebar on the computer to stop a sound that was uncomfortably loud. Reliability of responses was noted to be higher using this method than a pointing response to a loudness scale with "too loud," "good," and "soft." Further loudness balancing with sweeps across groups of three consecutive electrodes was trialed with the younger children but found to yield unreliable results. Children under 8 yr of age tended to find the task of comparing loudness across electrodes very difficult.

**Electrode Discrimination** • Electrode discrimination ability was measured using two reference electrodes: one in an apical region corresponding to a frequency range in the child's processor that incorporated 600 Hz, and the other in a mid-region of the array corresponding to a frequency range that incorporated 1500 Hz. The basal region was not investigated given recent findings by Henry et al. (1997) and Henry et al. (2000) with adults and Busby and Clark (2000) with early-deafened subjects, which suggest that electrode discrimination in this region is not significantly associated with speech perception ability. The duration of all stimuli was 300 msec, the interstimulus interval was 500 msec and the pulse rate was 250 pulses/sec. The task employed the procedure used in the SFT, which assesses discrimination of speech features in natural voice, computer controlled CV syllables (Dawson et al., 1998). This procedure was a modification of play audiometry and the change/no change task (Carney, Osberger, Carney, Robbins, Renshaw, & Miyamoto, 1993). The test procedure was found to be a useful tool for assessing 2- to 4-yr-old severely to profoundly deaf children, including children with cochlear implants.

In the SFT, the child performs a game-like motor response when a repeating background stimulus such as /ba/, changes to a different stimulus such as /pa/. As soon as the child enters a ready state of listening (is attentive and waiting to perform the fun motor response), a computer key is activated to begin a "wait" period, which is followed by the first trial or presentation of a change stimulus. The background stimulus is presented prior to the child entering a ready state, to prevent the child confusing the task with hearing acuity testing and hence responding to the onset of sound.

In the electrode discrimination task the child is taught to respond when a repeating stimulation on a reference electrode changes to stimulation on a different electrode after a variable waiting time. Six trials or change presentations occur for each electrode pair tested (reference versus comparison electrode), and the child receives a score out of 6 for the number of correct responses (hits). The criterion for successfully discriminating an electrode pair depended on the probability of a false positive response occurring in the hit window. False positive response rates (per second) are calculated by dividing the number of false positive responses occurring during the total waiting time over the six trials, by the duration of the total waiting time in seconds (i.e., total time excluding the "hit" windows). The probability that a false positive response would occur during a hit window (i.e., the child responds without actually discriminating the change) is then consid-

ered to be equal to the false positive rate multiplied by 4.2 sec, the length of the hit window. A simplifying assumption is made that the false positive rate is a constant. The binomial distribution was used to determine whether performance for an electrode pair was significantly above chance. A score of  $\geq 4/6$  represented a "pass" and was significantly above "chance" performance at  $p < 0.05$ , when the probability of a false positive occurring in the hit window did not exceed 0.26. If this probability was higher, a higher score than 4/6 was required to achieve the 95% confidence limit. A more detailed description of the procedure and stimulus presentation format can be found in the original publication of the SFT procedure by Dawson et al. (1998).

During the training phase the timing of presentation of stimuli was under tester control to ensure optimum flexibility. Initially the apical region of the cochlea was assessed. An electrode, four electrodes apical to the reference, was chosen as the "change" electrode and the tester "shaped" the child to wait and respond with the motor response to the change stimulus. "Shaping" involved the tester having his or her hand over the child's hand and performing the game-like responses for the child. The child's response was shaped four times in this way. When three consecutive independent responses occurred, random variations in stimulus levels were introduced to minimize the possibility that a child was responding to the change on the basis of loudness differences between the reference and comparison electrodes. Initially the levels ranged from 0% to 10% of an electrode's dynamic range below the C levels and increased to 40% at which all testing occurred. Most children continued to respond with 40% level jitter within minutes of training with the exception of Child 14 who needed a gradual introduction of the jitter over two sessions. In some cases a greater separation than four electrodes between reference and comparison electrodes was needed in training to ensure the child performed at or close to 100% accuracy.

A psychometric curve (of discrimination ability versus electrode separation) was obtained in apical and mid regions of the cochlea with testing at four to five different electrode separations. It included testing at a designated wider electrode separation and at progressively smaller separations until performance was no longer significantly above chance. For each of the smaller electrode separations tested, two practice items with feedback were provided to ensure that the child understood task requirements in light of the possible decreased saliency of the change stimulus. If performance was consistently high ( $\geq 5/6$ ) at all electrode separations of one to four electrodes from the reference, retest data were not

**TABLE 2. Acoustic characteristics of speech contrasts.**

Speech Contrast	Syllable Duration	FO (Start)	FO (End)	Consonant Duration (msec)	F1	F2
Vowel height						
ba	515	240	237	16	800	1360
bi	509	243	243	13	400	2400
Vowel place						
bi	503	242	240	6	360	2360
bu	516	247	242	12	400	1560
b $\Lambda$	218	240	240	12	800	1280
b $\text{v}$	218	240	240	10	680	960
Consonant voicing						
ba	515	240	237	16	800	1360
pa	506	247	240	56	800	1360
ta	497	247	242	59	840	1320
da	494	247	242	13	840	1320
Consonant place						
ba	506	240	234	8	800	1360
ga	503	237	235	9	760	1400
ba	497	242	242	16	800	1320
da	494	250	242	21	840	1320
ta	512	245	243	87	840	1360
pa	515	240	240	88	840	1360

Note: The background syllable appears first in order in each pair. The 1<sup>st</sup> and 2<sup>nd</sup> formants of the vowels are represented as F1 and F2.

collected. This decision was made to minimize testing time, given the young ages of many of the children.

When a child failed an electrode separation (scored <4/6) a conditioning check was done to ensure that the child had not failed because of a loss of conditioning. In this check, a trial was presented from a wider electrode separation that the child had previously discriminated successfully. If the child did not respond correctly, the failed score was not accepted and a training phase was reintroduced to re-establish conditioning. For children who failed an electrode separation and were still conditioned, testing was repeated in another session to determine performance reliability. If the retest score was also <4/6, the final score was taken as the mean of the two scores. If the electrode pair was successfully discriminated in the retest, further retesting was conducted. If a learning curve was evident, the final score was taken as the mean of the scores where performance had plateaued. Otherwise the final score for the condition was taken as the mean of the multiple tests for that electrode pair. The smallest electrode separation at which the child scored significantly above chance with an average of  $\geq 4/6$ , was defined as the smallest discriminable electrode separation (SDES) for that reference electrode.

**Speech Feature Test** • The SFT included eight speech contrasts: three vowel pairs and five stop consonant syllable pairs, two involving a voicing contrast and three involving a place of articulation contrast. Table 2 details the acoustic characteristics for the contrasts, measured on the Kay spectrograph

(Model 5500). Stimuli spoken by a female speaker were recorded directly onto a computer (16 bit PCM format) with a Pro audio spectrum 16 sound Card and a Shure SM57 Dynamic microphone. They were produced as individual digital audio files with a sampling rate of 22 kHz. Overall syllable length was matched as closely as possible in each of the contrasts. The speaker produced several tokens and those that were the best match were chosen. Similarly fundamental frequency (Fo) at the start and end of the syllables in each of the contrasts was matched as closely as possible in this way. A natural vowel quality was achieved by fading the waveform envelope at the end of the stimuli. An interstimulus interval of 800 msec occurred between syllables. Syllables were RMS equalized. In a departure from the original administration of the SFT in the study by Dawson et al. (1998), random level jitter of up to 6 dB was used for the background and change stimuli, to further minimize the possibility of a child using overall loudness cues in discrimination of the speech syllables.

In each of the contrasts one of the CV syllables acted as a "background" stimulus and the other as the "change" stimulus. The background stimulus remained the same where possible. In the test phase six trials or change presentations were presented for each of the eight contrasts with a total of 48 trials per subject. As in the psychophysical tasks, testing of each contrast began with two practice trials in which feedback was given. For each child testing began with the easiest contrast /ba/bi/ followed by a random ordering of the remaining contrasts.

**Closed-Set Word Recognition** • A taped version of the closed-set monosyllabic word test, the Picture Vocabulary test (Plant, 1984), was presented in the audition alone condition. It consists of 12 monosyllabic words in a 12-alternative forced-choice paradigm. Each item was presented twice in random order and the child was required to point to the picture representing the target word.

**Nonverbal Intelligence** • The nonverbal scale of the Kaufman Assessment Battery for Children (K-ABC) was used to assess the nonverbal intelligence of the children using cochlear implants (Kaufman & Kaufman, 1983). It was primarily administered to investigate the possibility that poor performance on psychophysical assessments could reflect poorer intellectual functioning, which causes greater difficulty in learning new tasks. The K-ABC nonverbal scale provides an estimate of intellectual potential for children aged 4 to 12.5 yr who exhibit communication problems and is useful for assessing hearing-impaired children (Ulissi, Brice, & Gibbins, 1989). The nonverbal scale produces a standard score with a mean of 100 and standard deviation of 15. The test assesses skills such as visual memory, spatial ability, problem solving and reasoning ability. There are a different group of subtests for children in three age ranges: 4.0 to 4.11 yr, 5.0 to 5.11 yr, and 6.0 to 12.5 yr. Two subtests, "Triangles" and "Hand Movements," were common to each age group. The nonverbal scale correlates quite well with the full scale and the performance scale of the Wechsler Intelligence Scale for Children with correlations between 0.60 and 0.70 (Kaufman & Kaufman, 1983; Wechsler, 1974).

## RESULTS

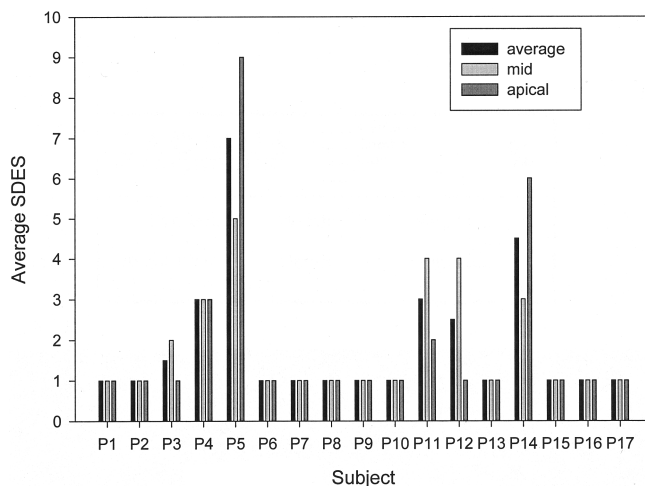
### Ease and Efficiency of Psychophysical Testing

An adaptation (Dawson et al., 1998) of the play audiometry procedure was found to be effective in assessing electrode discrimination ability in young children using cochlear implants. The time taken to complete the electrode discrimination task ranged from 25 to 60 minutes with a mean of 40 minutes.

The mean probability of a false positive response occurring in the hit window for the electrode discrimination task was low (0.043). The standard deviation was 0.089. The confidence level for scores  $\geq 4/6$  with this average probability is greater than the criterion of 95%.

### Electrode Discrimination

Figure 1 indicates that 13 of the 17 children showed ability to discriminate adjacent electrodes in



**Figure 1.** Average smallest discriminable electrode separations (SDES) as well as SDES for apical and mid reference electrodes are shown for the 17 children.

at least one region of the cochlea tested and 11 showed adjacent electrode discrimination in both regions. Six children revealed SDESs ranging from two to nine electrodes in at least one area of the cochlea. It should be noted that a floor effect was present, in that the best possible electrode discrimination was an SDES of one. For two of the children, apical SDES were larger than mid SDES and for three other children this finding was reversed. Child 12, despite being the oldest child in the study, had difficulty sustaining attention on the task and required frequent game changes to optimize his motivation. Child 3, Child 11, and Child 14 showed learning curves across sessions. Child 11 and Child 12 had nonverbal IQs more than one standard deviation below the normative mean (80 and 60, respectively).

### Speech Perception Closed-Set Tests

On the SFT, a repeated measures 1-way analysis of variance revealed that contrast type was a significant main effect ( $F(7,112) = 11.13; p < 0.0001$ ). Figure 2 shows that the mean discrimination scores for the vowel contrasts were higher than those for the consonant contrasts. A Student-Newman-Keuls multiple comparison test indicated significant differences between the vowel pairs and most of the consonant pairs with the exception of ba/ga. The discrimination of ba/ga was significantly better than the discriminations of ta/pa, ba/da, and ba/pa. The average SFT composite score was 77.6% with a standard deviation of 22.3%. Eleven children scored 90% or over on the Picture Vocabulary test. The mean score was 85.4% with a standard deviation of 19.5%.

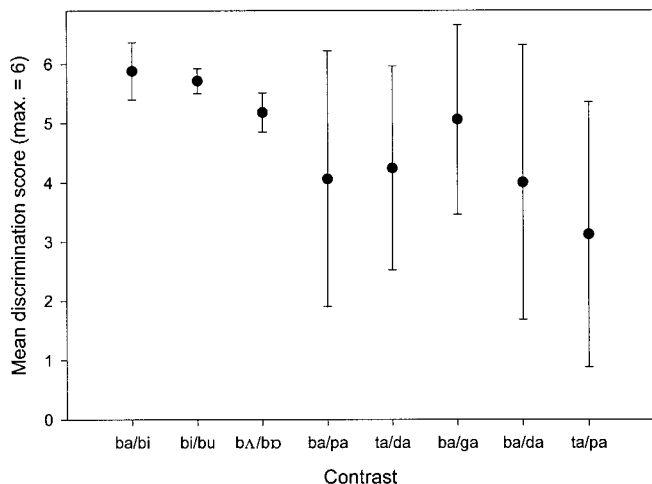


Figure 2. Mean discrimination scores and standard deviations for each of the speech sound contrasts for the children using cochlear implants.

**Nonverbal Intelligence**

The mean nonverbal IQ on the K-ABC was 98.14 with a standard deviation of 15.39. Three children (C11, C12, and C15), scored below 85, which is more than one standard deviation below the normative mean.

**Correlational Analysis**

The Pearson Product Moment Correlation was used to calculate correlations between the SDES and speech perception scores. Table 3 and Figures 3 and 4 indicate highly significant negative correlations between the average SDES (the mean of the apical and mid SDES) and the two speech perception measures; Picture Vocabulary test and the SFT. SDESs for both the mid and apical regions also correlated significantly with the speech perception measures. These significant negative correlations may have been influenced by the very low scores of Child 5 for electrode discrimination and speech perception. When the analysis was conducted with only 16 children, excluding this child, all correla-

TABLE 3. Pearson correlation coefficients between speech perception measures and average, apical, and mid smallest discriminable electrode separations (SDES) for the 17 children. Coefficients also were obtained for N = 16 children when the outlying subject was excluded and are shown in parentheses.

	Average SDES N = 17	Apical SDES N = 17	Mid SDES N = 17
Word recognition	-0.867 <sup>c</sup> (-0.611 <sup>a</sup> )	-0.859 <sup>c</sup> (-0.535 <sup>a</sup> )	-0.725 <sup>b</sup> (-0.527 <sup>a</sup> )
Speech Feature Test	-0.878 <sup>c</sup> (-0.814 <sup>c</sup> )	-0.803 <sup>c</sup> (-0.668 <sup>b</sup> )	-0.828 <sup>c</sup> (-0.756 <sup>c</sup> )

Coefficients marked with superscripts are significant. <sup>a</sup> p < 0.05; <sup>b</sup> p < 0.01; <sup>c</sup> p < 0.001.

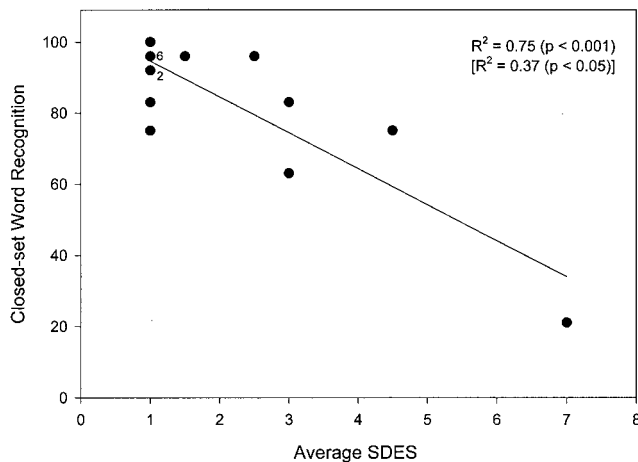


Figure 3. Children's percentage scores on the closed-set word recognition task as a function of their average smallest discriminable electrode separations (SDES). A linear regression line has been fitted. The variance accounted for, R<sup>2</sup>, and the level of significance, p, are shown on the graph for 17 children and in brackets for N = 16 children. The numbers next to the individual data points indicate the number of children with this tied score.

tions between electrode discrimination and speech perception scores were lower but remained significant, as seen in Table 3. The significant negative correlations between the average SDES and the composite speech feature discrimination score were predominantly due to the variability in the consonant discrimination performance. Figure 4 indicates near ceiling scores for the particular vowel pairs investigated in this study.

A forward stepwise regression analysis was conducted to determine the variance in the speech

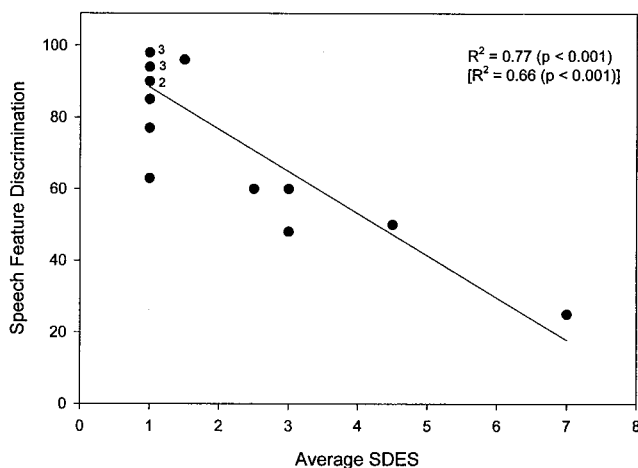


Figure 4. Children's composite percentage scores on the Speech Feature Test as a function of their average smallest discriminable electrode separations (SDES). The numbers next to the individual data points indicate the number of children with this tied score.

perception measures accounted for by the psychophysical ability and a number of subject variables. The latter included duration of profound bilateral deafness, age at implantation, age at testing, implant experience, age at onset of profound bilateral loss, number of electrode channels, communication mode (oral/aural versus total communication), overall nonverbal intelligence and performance on two IQ subtests, "Hand Movements" and "Triangles." The analysis was performed with 16 children (excluding the outlying patient, Child 5, who had the poorest SDES). Electrode discrimination (average SDES) was found to be the strongest predictor, accounting for 66% of the variance in the SFT performance and 37% of the variance in the closed-set word recognition task. Hand Movements was the only other variable that significantly accounted for some further variance (11%) in the SFT performance. Together these two variables accounted for 77% of the variance in the SFT scores.

A forward stepwise regression analysis was also conducted to determine whether any of the above-mentioned subject variables significantly accounted for variance in the scores on the electrode discrimination task. Communication mode was the only independent variable to account for a significant portion of the variance (24%) in the electrode discrimination task ( $N = 17$ ). Those children in the aural/oral educational setting had better electrode discrimination performance on average than those children in the total communication settings.

## DISCUSSION

### Electrode Discrimination

Average SDESs were less than 2.0 for 12 of the 17 children seen, but ranged from three to seven electrodes for the remaining children. This finding is consistent with electrode position difference limens reported for 16 early-deafened subjects aged 8.7 to 21.7 yr in the study by Busby and Clark (2000). This was despite methodological differences between the studies and large differences in the average duration of deafness and age of implantation of the patients in the studies. The mean duration of deafness and age at implantation were 8.75 yr and 9.3 yr, respectively, in the Busby and Clark study compared with 3.25 yr and 3.58 yr in the present study. The variability of electrode discrimination performance in the present study is also similar to the variability of performance reported for postlingually deafened adults (Henry et al. 2000; Nelson et al., 1995; Throckmorton & Collins, 1999; Zwolan et al., 1997). For example Zwolan et al. (1997) reported that the ability to discriminate electrode position in 11 postlingually deafened adults using the Cochlear

Ltd cochlear implant, varied greatly across patients. Some patients showed perfect discrimination of all electrodes whilst others showed very poor discrimination, requiring substantially larger separations than one electrode in some parts of the array to achieve approximately 71% accuracy in discrimination.

As in the study by Busby and Clark (2000), some children in the present investigation had much poorer electrode discrimination. Both studies found that lower closed-set speech perception scores were significantly associated with poorer electrode discrimination in the apical region of the cochlea. In contrast to Busby and Clark's findings, this study also observed a significant correlation between speech perception scores and electrode discrimination in the mid region of the cochlea. In her study of postlingually deafened adults, Henry et al. (2000) reported a significant correlation between phoneme open-set speech perception scores and electrode discrimination ability for low-mid frequency electrodes mapped to frequencies in the range 170 to 2680 Hz.

The relationship between electrode discrimination and speech feature discrimination was much more robust than that between electrode discrimination and closed-set word recognition. Only two children had word recognition scores outside the range of the group with an SDES of 1. Furthermore the variance in word recognition accounted for by electrode discrimination dropped from 75% to 37% when Child 5's data were removed (see Fig. 3). The SFT task was shown to be a more difficult task than the word recognition task and had a greater spread of scores.

The present study did not include open-set speech perception testing, because clinical files for the children indicated very restricted language ability for several of the younger children. The speech feature discrimination test is a useful test with preschoolers because it is not highly influenced by the child's ability to use linguistic information and attempts to measure the child's pure auditory capacity. Although necessary, good phoneme discrimination is not alone sufficient for good open-set sentence perception. Other factors such as the language ability of the child can have a substantial impact on open-set speech perception performance (Sarant, Blamey, Cowan, & Clark, 1997). Busby and Clark (2000) acknowledge that the influence of the child's language ability may help to explain the absence of a significant association between open-set speech perception scores and electrode discrimination ability in their study.

In keeping with the findings of Busby and Clark (2000), electrode discrimination ability in the apical and mid regions was not associated with subject



variables such as implant experience, duration of deafness and age at implantation in the present investigation. It should be remembered that the subject sample was small in both of these studies. Busby and Clark did report that subjects with a longer duration of deafness, who were implanted at a later age and tested at a later age, tended to have larger average and basal electrode difference limens. The subjects in both studies had at least 1 yr of implant experience. It is possible that implant experience is critical to electrode discrimination in the first few months postimplantation. The procedure used in the present study could possibly help to address this question and enable us to measure electrode discrimination over time in the first few months postimplantation in some young children.

Mode of communication did explain a small portion of the variance in the electrode discrimination scores in the present study. It is possible that children with poorer electrode discrimination may have demonstrated poorer oral/aural skills and as a consequence been more likely to have been placed in an educational setting with a manual supplement. Alternatively it is possible that a greater use of audition in an oral/aural educational setting may lead to an improvement in electrode discrimination ability.

### **Relationship of Subject Variables to Speech Perception Performance**

Unlike the study by Busby and Clark (2000), the present study found that electrode discrimination ability was the strongest factor in accounting for variance in the speech perception performance. In contrast to previous studies, the factors of duration of deafness, age at implantation, onset of profound loss and implant experience did not account for significant variance in the speech perception scores in this investigation. This could be at least partly explained by the fact that all of the children were implanted at a relatively young age ( $\leq 6$  yr) and had a short duration of profound deafness relative to that for children in previous studies. Furthermore the majority of the children were congenitally deafened and all were deafened before 2.5 yr of age. There is another possible interpretation of the findings. This study used speech feature discrimination and closed-set word recognition tasks, which are influenced less by the child's linguistic skills than open-set speech perception tasks. It is likely that linguistic skills are strongly influenced by factors such as duration of implant experience. Finally it should be remembered that the sample size for this study was relatively small and definitive statements

about the predictive value of any particular variable cannot be made in light of this.

Several studies with groups of children using either single-channel or multi-channel devices, have reported better speech perception scores for those in oral/aural educational programs than for those in total communication programs (Berliner, Tonokawa, Dye, & House, 1989; Dowell et al., 1997; Sarant, Reference Note 1). Similarly in this study there was a significant correlation between mode of communication and speech feature discrimination performance. Nevertheless a regression analysis revealed that mode of communication did not account for variance in the speech feature perception performance additional to that accounted for by the main factor, electrode discrimination. This was because communication mode was correlated with electrode discrimination ability; those children with poorer electrode discrimination ability were in the total communication programs.

Nonverbal intelligence has been measured previously in studies with children using cochlear implants and shown to be typically within the average to upper average range (Geers & Moog, 1991; Quittner, Thompson, & Steck, 1991; Tiber, 1985). The children in the present study performed very close to average. Little is known about the value of nonverbal intelligence in predicting hearing-impaired children's performance on speech perception and psychophysical tasks. Crandell (1991) believes that variability in speech recognition performance in adults can be attributed to three factors; 1) decreased psychoacoustical processing due to cochlear damage; 2) central auditory processing disability; and 3) deficits in cognitive skills such as learning, memory and reasoning. Quittner et al. (1991) reported that there was no relationship between overall performance IQ and the use of the cochlear implant in everyday life as measured by the Meaningful Auditory Integration Scale for 21 children using either a single-channel or a multi-channel device. However, they did find that certain subtests in the Wechsler Intelligence Scale for Children (Block Design and Picture Arrangement) did correlate with more optimal implant usage.

The estimate of nonverbal intelligence was not related to performance on the speech perception tasks for the 17 children in the present study. One of the subtests, Hand Movements, did, however, account for a significant amount of additional variance in the speech feature discrimination scores. This task requires the child to copy a series of hand movements in correct sequence. Although there is no obvious explanation for this correlation, performance on this test was found to influence articulation and oral receptive vocabulary in 70 prelingually

deaf children aged 3.5 to 4.25 yr and in 135 prelingually deaf children aged 4 to 6 yr (Broesterhuizen, 1997). The interrelated skills of fine motor ability for hand and mouth, sequential memory and memory for rhythm were reported to be more important than hearing loss, in predicting articulation and oral receptive vocabulary in these children. The Hand Movements test of the K-ABC was one of the tests used to assess these skills, which, in combination, were referred to as "eupraxia": the ability to quickly recall and skilfully automatize movements (Van Uden, 1983). Gallaway, Aplin, Newton, and Hostler (1990) observed that performance IQ was mildly but significantly correlated with spontaneous language level, as measured with Mean Length of Vocalizations and Verbalizations, for 79 mild-profoundly hearing-impaired children aged 3 to 7 yr. Further research on the relevance of cognitive skills and general nonverbal intelligence would be needed to clarify the role of these skills in predicting successful performance with the cochlear implant in speechreading, speech perception and language.

Other factors that were not measured in this study could possibly account for further variance in the speech perception scores. Those children with SDEs of 1 or 1.5 still showed a range of scores on the speech discrimination task. It is possible that some of these children may have poorer electrode discrimination in other areas of the array that were not measured and that pitch reversals may exist (Busby et al., 1994; Nelson et al., 1995). Differences in temporal resolution ability may account for some of this variance. Finally it should be noted that one of these children with adjacent electrode discrimination used the Multipeak strategy in contrast to the Speak strategy that was used by all of the other children. This difference in strategy may help to explain the relatively poorer composite speech discrimination score for this child.

### Practical Implications/Future Directions

Research has repeatedly shown that electrode discrimination is poorer for some children and for some adults using cochlear implants. Some research has been done to evaluate strategies aimed at improving discrimination of electrodes, such as removal of nondiscriminable electrodes from the speech coding (Collins et al., 1997; Zwolan et al., 1997). More work needs to be done to clarify the benefits of such strategies. Such work with adults may guide us in helping young children who have been identified as having poorer electrode discrimination ability. It is possible that poorer electrode discrimination ability is partially due to a less finely tuned tonotopic map in the auditory cortex. If this

were the case, intensive psychophysical training in discriminating electrodes and/or speech stimuli training that emphasizes spectral differences in speech sounds could possibly improve electrode discrimination. Cortical plasticity studies with monkeys indicate that a period of intensive training can improve fine temporal and spectral distinctions (Merzenich, Schreiner, Jenkins, & Wang, 1993).

The child-appropriate procedure used in this study allows us to measure electrode discrimination ability in younger children who are not progressing as well as expected. If a problem in electrode discrimination is identified early, it could be addressed during those critical years of language development. It is likely that the procedure trialed in this study could also be suitable for children as young as 2 yr of age, given that the speech feature discrimination procedure (SFT) was successful in assessing speech discrimination in many 2- to 3-yr-old profoundly deaf children. Future work could use the procedure to address plasticity issues; in particular the effect of electrical stimulation on electrode discrimination ability in the months directly after implantation.

### CONCLUSIONS

Electrode discrimination ability was able to be effectively assessed in young children using an adaptation (Dawson et al., 1998) of the well-known play audiometry procedure used in hearing acuity testing. The ability to discriminate electrodes in the mid and apical regions of the cochlea was the strongest factor in predicting speech feature discrimination and closed-set word recognition in children aged 4 to 10 yr.

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