Changes in Synthetic and Natural Vowel Perception after Specific Training for Congenitally Deafened Patients Using a Multichannel Cochlear Implant

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Objective: The aim was to determine whether the ability to use place-coded vowel formant information could be improved after training in a group of congenitally deafened patients, who showed limited speech perception ability after cochlear implant use ranging from 1 yr 8 mo to 6 yr 11 mo. A further aim was to investigate the relationship between electrode position difference limens and vowel recognition.

Design: Three children, one adolescent, and one young adult were assessed with synthesized versions of the words /hid, head, had, hud, hod, hood/ containing three formants and with a natural version of these words as well as with a 12-alternative, closed-set task containing monosyllabic words. The change in performance during a nontraining period was compared to the change in performance after 10 training sessions.

Results: After training, two children showed significant gains on a number of tests and improvements were consistent with their electrode discrimination ability. Difference limens ranged from one to three electrodes for these patients as well as for two other patients who showed minimal to no improvements. The minimal gains shown by the final patient could be partly explained by poorer apical electrode position difference limen.

Conclusions: Significant gains in vowel perception occurred post-training on several assessments for two of the children. This suggests the need for children to continue to have aural rehabilitation for a substantial period after implantation. Minimal improvements, however, occurred for the remaining patients. With the exception of one patient, their poorer performance was not associated with poorer electrode discrimination.

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Studies seem to concur that many children and adolescents implanted with the 22-electrode cochlear implant achieve significant open-set speech perception performance (Dawson et al., 1992; Gantz,

Tyler, Woodworth, Tye-Murray, & Fryauf-Bertschy, 1994; Miyamoto, Osberger, Robbins, Myers, Kessler, & Pope, 1992; Tyler, 1990; Waltzman, Cohen, Gomo-lin, Shapiro, Ozdamar, & Hoffman, 1994). In contrast, there are many early-deafened implant users who do not achieve open-set speech perception. These less successful users may not be able to utilize the spectral information offered by the implant effectively. In a multichannel cochlear implant, spectral information in speech sounds is coded by stimulating different electrodes. To what extent can poorer performers use this place-coded information and benefit from specific training which emphasizes spectral differences?

To investigate these questions this study focused on the ability of poorer performers to utilize formant information in vowel perception. It is well documented that the 22-electrode cochlear implant encodes the formants or spectral peaks of vowels by stimulating different electrodes (Blamey & Clark, 1990; Blamey, Dowell, Brown, Clark, & Seligman, 1987; Skinner et al., 1991). Synthetic vowels were used because the formant frequencies can be specified in terms of the electrodes stimulated and loudness, duration, and F0 parameters can be kept constant. Previous research by Blamey and Clark (1990), Tyler, Tye-Murray, Moore, and McCabe (1989) and Tyler, Tye-Murray, & Otto (1989) has indicated that patients implanted with multichannel cochlear implants can utilize place-coded information in synthetic vowel recognition. Natural vowel identification involves the use of a number of acoustic cues, including differences in amplitudes of formant peaks, in fundamental frequency (F0), and in the duration of the vowels as well as differences in formant frequencies. Blamey and Clark (1990) in their study of four postlinguistically deafened adult patients using the 22-electrode implant, found that natural vowels with the additional cues of loudness, duration, and F0, were more easily recognized than synthetic vowels.

Vowel perception will be less effective if stimulation of electrodes at different places in the cochlea does not result in sounds which can be discriminated. The question then arises; is the poorer speech perception performance of some implant users associated with poorer electrode discrimination or recog-

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nition? Busby, Tong, and Clark (1993) found that improvement in speech perception performance from a single-electrode strategy to a multielectrode strategy was related to successful discrimination of trajectories with time varying electrode positions. Only one of the four early-deafened patients assessed showed good electrode discrimination and improved speech perception when the first and second formants (F1 and F2) were encoded as time varying electrode positions. This child was implanted earlier than the other patients, at 5 yr of age.

Busby, Tong and Clark (1992) found that the poor psychophysical performance of two early-deafened patients implanted after the age of 10 yr was consistent with their poor vowel identification performance. These patients could not consistently identify electrodes separated by four electrodes. Their vowel perception scores in the identification of 11 vowels were at the lower end of the range of scores reported for 26 postlinguistically deafened adults (22 to 68%) by Blamey et al. (1987).

A positive, linear relationship between speech recognition and electrode discrimination or recognition should not necessarily be expected, however. Poor speech perception performance may coexist with good electrode discrimination. Other factors can limit speech perception performance. As the speech perception task becomes more complex and requires a higher level of cognitive processing, it becomes less like the psychophysical task. The measurement of electrode discrimination or identification usually involves listening to one electrode at a time, whereas the word recognition task involves listening to several electrodes at once, the exact number depending on the processing strategy used. It is possible that electrode interactions could cause a reduction in sensitivity to electrode position in the speech task which involves multiple electrode stimulation (Shannon, 1983; Tong & Clark, 1986).

To investigate the relationship between electrode discrimination and word recognition more carefully, the speech stimuli used should approximate the psychophysical stimuli. Vowels are the speech sounds closest to steady-state stimuli. Synthetic vowel perception was assessed in this study and discussed in relation to electrode position discrimination. The measurement of difference limens in this investigation used the adaptive technique described by Busby and Clark (1996) and random variations in amplitude to minimize the availability of loudness cues for electrode discrimination.

If, in fact, vowel recognition performance is poorer than expected on the basis of the measured electrode discrimination, one would predict potential for improvement in vowel perception with training. This study aimed to improve the ability of five

congenitally deafened patients to use place-coded formant frequency information in vowel perception through specific training. There are few studies which have attempted to assess the benefits of specific training for children and adolescents using multichannel cochlear implants. Many studies have reported that multichannel implantation in conjunction with extensive aural/oral training has led to improvements in the speech perception of implanted children and adolescents (Dawson et al., 1992; Tyler, 1990; Waltzman et al., 1994). In these studies, however, the influence of the training cannot be separated out from the influence of the device, training in the educational setting, and maturation. In a specific training study, Busby, Roberts, Tong, and Clark (1991) did not observe significant individual gains in vowel perception after three analytical training sessions for three prelinguistically deafened patients (two adults and one adolescent) using the 22-electrode cochlear implant with an F0F1F2 strategy.

The following main question was investigated: 1) would there would be significant improvement in vowel perception performance after training, compared to a nonsignificant change in performance during pretraining phases? Additional questions were: 2) would gains in vowel perception generalize to a higher order task of word recognition? 3) would skills acquired after training be retained after removal of the training? and 4) what is the relationship between vowel perception ability and electrode discrimination?

METHODS

Patients

The group of patients included three children, one adolescent, and one young adult whose ages ranged from 8 yr 6 mo to 21 yr 10 mo at the time of testing. They were implanted with the 22-electrode cochlear implant at the Royal Victorian Eye & Ear Hospital after a duration of deafness of at least 4 yr. They had used the implant for periods ranging from 1 yr 8 mo to 6 yr 11 mo before data collection. None have achieved open-set speech perception performance or scored above 60% on a 12-alternative, monosyllabic word recognition task. Table 1 gives individual details. Preoperative average hearing loss in the better ear is expressed as pure-tone average hearing loss (PTA) in dB HL. Patient 5 used a multichannel electrotactile aid ("Tickle-Talker," Cowan, Blamey, Galvin, Sarant, Alcantara, & Clark, 1990) in addition to a hearing aid before implantation and Patient 2 used the two-channel vibrotactile Tactaid II (Audiological Engineering, Somerville MA). For 2 yr postimplantation Patient 3 continued to use a hearing aid on the unimplanted ear after which time he rejected it.

TABLE 1. Patient details

Patient	Etiology	Age at Testing	Current Educational Program	Age at Implantation	PTA Loss Better Ear	Mode of Stimulation	No. of Channels	Duration of Implant Use
1	Usher's syndrome	21 yr 10 mo	Employed	14 yr 11 mo	115	Common ground	20	6 yr 11 mo
2	cytomegalo virus	10 yr 6 mo	Total Communication	4 yr 7 mo	116	Common ground	20	5 yr 11 mo
3	Unknown	10 yr 5 mo	Total Communication	7 yr 9 mo	115	Common ground	21	2 yr 8 mo
4	Unknown	8 yr 6 mo	Total Communication	6 yr 7 mo	110	Common ground	22	1 yr 11 mo
5	Genetic	15 yr 2 mo	Cueing Supplement	13 yr 6 mo	>120	Bipolar + 1	20	1 yr 8 mo

The current educational program of three of the patients was total communication in which signed English was used. Patient 5 was in an auditory/oral program which used a cued speech supplement. Similarly, Patient 1 was educated with cued speech before employment. Patients 2 and 4 were previously in auditory/oral early intervention programs, and Patient 3 received an auditory/oral education until 7 yr of age. Learning difficulties and cognitive processing problems were reported for Patient 2 in a neuropsychological assessment. There were no known cognitive or learning deficits for the other patients.

The patients were implanted with the 22-electrode cochlear prosthesis (Clark et al., 1987). For Patient 5 the stimulation was between pairs of electrodes 1.5 mm apart, with one electrode band in between. For the other patients the "common ground" mode of stimulation was used. In this mode the current flows between a single "active" electrode and all remaining electrodes connected together. Patients used the mini speech processor with a multipeak strategy encoding F0, F1, and F2, as well as three high frequency bands: 2.0 to 2.8 kHz (Band 3), 2.8 to 4 kHz (Band 4), and frequencies above 4 kHz (Band 5) onto three fixed basal electrode positions (Skinner et al., 1991). The signal amplitudes in these regions are measured and the encoding strategy generates four pulses of electrical stimulation per stimulus period.

After implantation the patients received habilitation additional to that provided in their educational programs for at least 1 yr. Patients 1 and 2 received 3 to 4 yr of habilitation. The training usually involved individual sessions of approximately 1 hr per wk. It focused on the use of audition in the development of spoken communication.

General Design

In a single-subject design, each subject acted as his or her own control, given that the change in performance during at least one pretraining period was compared to the change in performance after a 10 wk training period. Four of the patients were assessed during two pretraining periods ranging from 12 to 28 wk in duration. The remaining patient was assessed before and after one pretraining period

lasting 18 wk. The retention of skills after direct training has ceased is naturally desirable. In the present study an additional post-training assessment was conducted 3 wk after the cessation of the training, to determine whether or not skills acquired immediately after training were retained. It was unable to be conducted any later than this because most of the patients were changed over to the Spectra processing strategy (Skinner et al., 1994) 4 wk after the conclusion of the training program.

Difference limens for electrode discrimination were measured over a few sessions for each patient immediately before the pretraining period. When there was poorer minimal pair vowel perception than expected given the measured electrode discrimination, minimal pair assessments were repeated at the commencement of the training program using an older processing strategy "F0F2" in which only one electrode, representing the second formant, is stimulated per pulse. For example, if performance on the highly contrastive vowel pair (hid/hood) was not significantly above chance, despite electrode position difference limens of one to two electrodes, the assessment would be repeated using the older strategy. The rationale for this was to investigate the possibility that electrode interactions may result from overlapping current distributions from the electrodes stimulated in the multipeak strategy. Such interactions may degrade performance causing stimuli to sound more similar (Shannon, 1983; Tong & Clark, 1986). Furthermore, better performance with the older strategy has been reported for some patients on closed-set recognition tasks previously (Blamey & Clark, 1990; Tye-Murray, Lowder, & Tyler, 1990). All patients were re-assessed using this older strategy, given that at least some mismatch occurred between minimal vowel pair recognition and the difference limens measured.

Assessment

Balancing Loudness Comfort

Before any assessments, the stimulus levels of the individual electrodes were initially adjusted to be equally loud at the maximum comfortable listening

level (C level). Loudness imbalance between electrodes is undesirable as it could allow the patients to use loudness cues to differentiate between vowel sounds. Sound amplitude was coded using the stimulus level scale. Over most of the stimulus level range (65 to 229 levels) the current amplitude is constant at 1000 μ A and the pulse width changes exponentially. This increase in pulse width is associated with a rise in perceived loudness. In the lower and upper part of the stimulus level scale the pulse width remains constant and current amplitude rises exponentially (Skinner et al., 1991).

C levels were measured using an ascending-descending technique. The stimulus level was increased until stimulation was reported to be too loud and then decreased to a level corresponding to the maximum comfortable listening level. Time was then spent in balancing the loudness of the comfort levels, to ensure that the electrodes were approximately of equal loudness. Initially a group of three electrodes was presented and the patient indicated whether any of the electrodes required adjustment to achieve equal loudness. This procedure was repeated for consecutive groups of three electrodes, with an overlap of one electrode from the previous group, until all electrodes had been checked. Second all electrodes were presented in an apical-basal direction and the patient was asked to indicate the need for further adjustments.

Difference Limens for Electrode Discrimination

Psychophysical Procedure • The aim of the psychophysical study was to measure electrode discrimination ability. The patient was asked to discriminate the odd-man out in a forced-choice adaptive procedure (Busby & Clark, 1996). Two of the stimuli were the reference electrode and the third was the comparison electrode. The patient used a "mouse" to select the number on the computer screen which corresponded to the interval with the comparison in each trial. After each trial, feedback was given by flashing the number on the screen which corresponded to the comparison. Unlike Busby and Clark who assessed difference limens for three reference electrodes, only two regions of the cochlea were assessed in this study because of time constraints in withdrawing the children from the classroom. Reference electrode 18 was used for the apical region and electrode 11 for the basal region. The comparison electrode was always basal to the reference electrode.

A simple "two down, one up" procedure typically used in psychoacoustic testing and described in detail by Levitt (1970) was employed. Each "run" began with the comparison clearly different from the reference to make the task easy. The spatial separation

between the comparison and reference electrodes was reduced by one electrode (0.75 mm) after two correct responses and increased by one electrode after one incorrect response. Each run was terminated after 10 reversals and the mean of the final six taken as the difference limen. This converged on a spatial separation producing about 70% correct responses. The first three runs were used as practice runs allowing for patient learning effects.

Electric Stimulation Paradigm

The electric stimulation paradigm described by Busby and Clark (1996), in which loudness was varied across comparison and reference electrodes, was used in this study. The stimulus levels for the C levels were converted to current levels and pulse width levels for the psychophysical evaluation. Loudness variations were achieved by decreasing pulse width as a percentage of the difference between the lowest and highest pulse width levels. The decrease in pulse width was randomly determined for the reference stimuli and comparison stimulus in the forced-choice procedure. The decision to vary pulse width was based on the fact that pulse width rather than current level varied for the range of stimulus levels which were mapped as C levels in these patients. In the first block of stimuli no jitter or loudness variation was introduced. In successive blocks 3° of jitter were introduced, the final amount of jitter varying up to 50% of the range of pulse widths for the C levels. A pulse rate of 250 msec, a stimulus duration of 300 msec and an interstimulus duration of 500 msec were used.

Synthetic Speech Recognition

Six short vowels in an h_d frame were synthesized on a Klatt parallel speech synthesizer (Klatt, 1980). These were [i], [ε], [æ], [ʌ], [ɑ], and [u] in hid, head, had, hud, hod, and hood, respectively. The steady state formant frequencies of the first three formants, formant transitions, and the relative amplitudes of the formants were average values derived from three stimulus sets using the trainer's voice. Each vowel was 140 msec in duration (including the formant transition) and had a fundamental frequency falling from 240 to 210 Hz. The durations of the /h/and/d/ were 110 and 80 msec, respectively. The values of the first three formants; F1, F2, and F3 for the steady state vowels of each word are given in Table 2. The relative amplitudes for the formants for each vowel differed because they were chosen to match the speaker's amplitudes in an attempt to generate more "natural" sounding stimuli. The overall amplitude of the stimuli were, however, matched at 70 dB sound pressure level to within 1 dB.

TABLE 2. Formant frequencies used for the steady-state part of the synthetic vowel stimuli (Hz)

	F1	F2	F3
Hid	360	2413	3146
Head	440	2280	2780
Had	760	1900	2680
Hud	830	1380	2520
Hod	660	1080	2460
Hood	400	860	2280

The vowels were recorded and checked on a sonograph (Kay, Model 5500) to ensure that the spectral information approximated the natural voice parameters. A computer program was then used to determine the electrode selection for the formants for each individual. The latter would depend on the hardware estimation of frequency and amplitude parameters as well as the frequency boundaries of the electrodes in an individual's processor "map." The processor was connected via a direct audio-input to a tape recorder. The computer program plotted amplitudes on electrodes versus time, which indicated which electrodes were stimulated for the formants. Final modifications were made to the synthetic vowels to ensure as close a match as possible between the trainer's formant frequencies used for the steady state portion of the synthetic vowels and the frequencies stimulated by the electrodes given tape-recorded input via a direct audio-input. Figure 1 shows the "vowel spaces" in terms of the electrodes corresponding to the F1 and F2 frequencies of the synthetic vowels for each patient. The synthetic vowels were tried on two postlingually deafened adults using cochlear implants, to determine their intelligibility. The adults listened to the stimuli through their implants via direct audio-input from a tape recorder. They scored 96 and 92%, respectively, when the six vowels were presented

four times each in random order in a 6-alternative closed-set task.

At each assessment patients were tested on six minimal synthetic vowel pairs (e.g., hid/hud) chosen to cover a broad range of electrodes and to include easy to difficult contrasts. For Patients 1 and 2 whose maps had the same electrodes, these pairs were the same. The minimal pairs were tested in a 2-alternative forced-choice recognition task with 20 items. The synthetic vowels were also assessed in a 6-alternative forced-choice format, in which each vowel occurred randomly four times, making a total of 24 items. Given the patients' unfamiliarity with synthetic speech stimuli, a complete practice list was used at the initial assessment for the six short, synthetic vowel test. At subsequent sessions each of the six short vowel stimuli were presented to the patient once before the test stimuli were presented. The same procedure was used for the six short, natural vowel test discussed below. The stimuli in the vowel pairs were presented three times each as practice items. No feedback was provided during any of the testing. The patient was asked to respond by pointing to cards labeled with the /h_d/ words. The words were presented audiovisually initially to ensure that the patient could correctly identify each word. For the nonsense words /hud, hod/ and for the less familiar words /hid and hood/ the younger patients drew a picture representing a familiar word which rhymed with the stimulus word (e.g., a picture of "wood being cut" was drawn next to "hood").

Natural Speech Recognition

Two tasks using natural speech stimuli were included in the assessments. First there was a six short vowel task using taped, natural stimuli spoken by the trainer. The Picture Vocabulary test (Plant, 1984) was the other task. It requires the recognition

Figure 1. Vowel spaces. Electrodes stimulated to represent F1 and F2 for the synthetic vowel stimuli for each patient.

of 12 monosyllabic words in a 12-alternative forced-choice format. The 12 words are shoe, fork, tree, car, bird, key, dog, book, duck, bed, hat, and fish. Each item was presented twice and the patient responded by pointing to a picture.

All speech materials were presented via direct audio-input (a cable taking a tape recorded signal directly into the processor). The direct input provided a frequency response with emphasis in the high frequencies similar to the cochlear implant's ear-level microphone's response. At each data collection time, two lists were conducted for the six short synthetic vowel and Picture Vocabulary tests. Unlike Patients 1 and 5, the three children received only one list of each of the minimal pairs per assessment because of their shorter concentration spans and time constraints in withdrawing them from classroom work. Different randomizations of the tests were used during the study to avoid the possibility of patients remembering ordering of the stimuli.

Training

General Methods

The training focused specifically on improving vowel perception. Although these patients had received habilitation in the past, the training had not been as specific and hierarchical as the training in this study. The trainer was a pediatric audiologist experienced in habilitation techniques. Training occurred once a week for 10 wk, resulting in a total of 10 sessions. Each training session was approximately 50 minutes in duration, incorporating 40 minutes of analytical exercises and 10 minutes of synthetic tasks.

The type of training program was similar to programs described in past research with hearing aid users and users of tactile devices (Alcantara, Cowan, Blamey, & Clark, 1990; Alcantara, Whitford, Blamey, Cowan, & Clark, 1990; Bode & Oyer, 1970; Busby et al., 1991; Rubinstein & Boothroyd, 1987; Tye-Murray, Tyler, Lansing, & Bertschy, 1990; Walden, Erdman, Montgomery, Schwartz, & Prosek, 1981). Training began with easier tasks (gross formant contrasts) and progressed to more difficult tasks according to the success of the patient. The number of alternatives provided in closed-set, forced-choice recognition tasks was increased as the patient's ability improved. Diphthongs were not included in the analytical training. Because natural intensity differences between the vowels were still available, the trainer often tried to alter these differences by deliberately making a softer vowel (e.g., [ɪ] or [ɛ]) more intense at times.

Varied activities and games were used to increase the motivation of the patients. This has been found to be important in previous training studies (Bode & Oyer, 1970; Tye-Murray et al., 1990b). Turn-taking (i.e., the child has a chance to be the teacher) has been deemed an important component of a training program (Bode & Oyer, 1970; Galvin, Cowan, Sarant, Blamey, & Clark, 1993). It was encouraged at all times in the present study. Another important aspect of training is that the stimuli being trained can transfer or generalize to untrained stimuli (Alcantara, Whitford, Blamey, Cowan, & Clark, 1990; Galvin et al., 1993; Robbins, 1990). In the present investigation this was considered in two ways. First, test words were not used in the training. Second, a word recognition task involving vowel and consonant cues was included in the assessments.

Description of Activities

The concept of rhyme was fundamental to the present training program because it focused the child on the vowel sounds. In one task patients were encouraged to generate words which rhymed and to put these new words into sentences. Rhyming words would, for example, be generated in two lists under the words /cat/ versus /cot/, whose vowels have contrasting formant information. The patient and trainer would take turns in thinking of a new word, without indicating which of the two lists the word was to go in. The patient would be given the target word via audition alone but the sentence was provided with lipreading and/or signed English as needed. The patient was encouraged to imitate the word. Given that rhyming greatly restricted the choice of words the task was then modified to include monosyllabic words which had the same vowel sound. For example "back" or "map" would be acceptable words to put into the list headed by the word cat with the [æ] sound. This allowed exposure to vowels in more varied contexts.

Another analytical task was a memory matching card game in which a group of cards (4 to 10 matching pairs) were placed face down in rows and the player had to try to turn over two cards with matching words and pictures. When it was the trainer's turn the cards were picked up without allowing the patient to see them. The patient was encouraged to listen and determine whether the words were the same or different, to imitate the words, and finally to guess the words after they were put into sentences. The winner was the player who collected the most pairs. Other games were "Lotto" in which four to six cards were on each board representing words which differed predominantly in terms of the vowel sound and "Fish," in which the player had to collect pairs of cards with matching

words and pictures. The young children enjoyed creating the Fish game by first thinking of monosyllabic words that rhyme, writing the words on cards, and drawing pictures to represent them. The task could be simple with rhyming words for only two contrasting vowels (e.g., knit, hit, kick, tick, sick versus hot, sock, rock, dot, cot) or difficult with rhyming words for a number of vowel sounds.

In a "Treasure Hunt" game envelopes were hidden around the room. When the child found one he or she would find a card inside with a monosyllabic word and picture on it. The child had to post the card in an appropriate box for words with the same vowel sound. For example, the word "ship" would go in the box representing [i] words. Again the task could be made simple with only two boxes representing contrasting vowels or harder with a larger and more difficult closed-set. The trainer deliberately included words with vowels that sounded the same but were spelled differently (e.g., sun and won). Board games were created such as a variation of Snakes and Ladders and a Space game with pictures of spaceships and rockets. If the patient landed on a space with a dot on it he or she had to pick up a card from a pile and think of a rhyming word. Rhyming songs were used such as "This Old Man" in which the patient was encouraged to think up different rhyming words for each number (e.g., this old man, he played three, he played nick knack on my knee/tree/tea/key). Finally, discrimination of monosyllabic words (same/different) or odd-man out tasks were used for a few minutes in each session.

The two adolescents were given these brief discrimination tasks as well as the memory and board games and creating lists of rhyming words. In addition, they were given more sophisticated tasks: generating poetry and a reading task. They were encouraged to read simple short stories which were about things of interest to them and which were loaded with lots of monosyllabic words incorporating target vowels. For example, if the patient was having difficulty discriminating [æ] from [ʌ], sentences such as "Max asked Pat to the dance" would be loaded with the vowel [æ]. Similarly there would be sentences loaded with the vowel [ʌ]. After reading the story once, the adolescents re-read it. They were encouraged to focus on the sound of these vowels and to write down groups of words in the story which shared the same vowel sound.

A different subset of the analytical tasks described was chosen each session for each patient to ensure variety and ongoing motivation. Training also included 10 minutes of synthetic or open-set training at the close of each session to facilitate integration of vowel feature information into the perception of running speech in natural situations.

TABLE 3. Electrode position difference limens for different reference electrodes. The means and ranges of difference limens obtained across varying degrees of jitter are shown

Patient	Reference Electrode			
	18	14	11	7
1	1.7 (1.5-1.8)	1.4 (1.0-1.7)		1.2 (0.8-1.3)
2	1.4 (1.3-1.5)		0.7 (0.5-0.9)	
3	1.8 (0.8-2.3)		1.8 (1.2-2.5)	
4	1.6 (1.2-1.8)		2.6 (2.3-3.0)	
5	5.7 (5.5-5.8)		1.7 (1.5-1.8)	

Short stories of interest to the patient would be told and a picture would be drawn as the story unfolded. The trainer sat side-on to the child to encourage reliance on auditory cues. Signing and lipreading cues were provided according to the needs of each child.

Data Analysis

A two-tailed Chi-square statistic ($p < 0.05$) was used to compare change in performance between assessments taken at the beginning and end of two pretraining periods, at the beginning and end of a training period and 1 wk versus 3 wk post-training.

RESULTS

Difference Limens for Electrode Discrimination

The mean electrode position difference limens shown in Table 3 for Patients 2, 3, 4, and 5 were the average difference limens obtained across several different degrees of jitter. Mean difference limens reported for Patient 1 with reference electrodes 18, 14, and 7 were obtained by Busby and Clark (1996) using a 50% convergence rule. For Patients 1 to 4, mean difference limens did not exceed three electrodes. In contrast, the apical difference limen for Patient 5 was almost six electrodes.

Synthetic Speech Recognition

Figures 2 through 6 indicate the mean performance on each assessment before and after pretraining periods and before and after a 10 wk training period for Patients 1 through 5, respectively. The electrode separations of the vowel pairs refer to the distances in terms of number of electrodes for the F1 and F2 for the vowel pairs. These distances were calculated as the lengths of vectors in a Euclidean space. The distance between a pair of vowels is therefore equal to the square root of the sum of squares of the F1 and F2 electrode separation.

All patients performed significantly above chance throughout the entire assessment period on at least

Figure 2. Patient 1's percentage performance on minimal vowel pairs, the six short vowel task using synthetic and natural vowels and the monosyllabic word test across pre- and post-training periods. The electrode separations of the vowel pairs (based on the F1 and F2 separation) are shown in italics. The area above the dashed line indicates performance which is significantly above chance at the 0.05 level. Significance levels refer to the Chi-square analyses of changes in performance between two consecutive assessments. a denotes $p < 0.05$; b denotes $p < 0.01$; c denotes $p < 0.001$ (see Figs. 3–6). There were no significant changes in performance for Patient 1.

two of the minimal vowel pairs assessed. These vowel pairs generally had contrasting formant information and were characterized by wide electrode separation (6 to 11 electrodes). Two patients, 1 and 5, showed no significant gains after training on the vowel pairs for which performance was not significantly above chance in the pretraining period. In contrast, Patients 3 and 4 showed significant gains on two of the three vowel pairs for which pretraining scores were not significantly above chance. Patient 2 showed a significant gain on one vowel pair /hud/hod/.

At the commencement of the training program, performance with an older processing strategy, F0F2, was measured. For Patient 1, performance with this strategy was excellent (95% or above) for all vowel pairs except /hud/hod/ (65%), in which the electrode separation for the F2 was only two electrodes. For the other patients, changing to the F0F2 strategy did not improve performance for minimal pairs which the patients had difficulty differentiating with the multipeak strategy. Given the improvement in minimal vowel pair perception with the F0F2 strategy, Patient 1 was also assessed on the six short vowel tasks and the Picture Vocabulary test with this strategy. Scores on these tasks were,

however, found to be very similar to scores on these assessments with the multipeak strategy.

With the exception of Patient 5, patients' performance on the six short synthetic vowel task was significantly better than chance across the assessment periods. Three of the patients (Numbers 3, 4, and 5) showed a significant gain 1 and 3 wk post-training (see Figs. 3 through 5).

Natural Speech Recognition

In line with the six short, synthetic vowel test, most patients' performance on the six short, natural vowel test was significantly above chance during assessments. Two patients (Numbers 3 and 5) showed significant increases after training (Figs. 4 and 6). Given time constraints, the natural vowels were not reassessed 3 wk post-training for Patient 3. The finding for Patient 5 loses impact, given the statistically significant decline in performance in the second pretraining period.

Similarly, although Patient 2 showed a significant gain after training on the monosyllabic word test, the performance after training was not significantly greater than the average pretraining perfor-

Figure 3. Patient 2's performance on minimal vowel pairs, the six short vowel task using synthetic and natural vowels and the monosyllabic word test across pre- and post-training periods.

Figure 4. Patient 3's performance on minimal vowel pairs, the six short vowel task using synthetic and natural vowels and the monosyllabic word test across pre- and post-training periods.

Figure 5. Patient 4's performance on minimal vowel pairs, the six short vowel task using synthetic and natural vowels and the monosyllabic word test across pre- and post-training periods.

Figure 6. Patient 5's performance on minimal vowel pairs, the six short vowel task using synthetic and natural vowels and the monosyllabic word test across pre- and post-training periods.

mance. Patient 3 revealed a highly significant gain 1 wk post-training on this test. This improvement was maintained 3 wk post-training.

Relationship between Vowel Recognition and Electrode Discrimination

Before training vowel and speech recognition was poorer than expected for Patients 1 through 4 given their electrode discrimination ability (see Table 3 and Figs. 1 through 5). After training, Patients 3 and 4 showed improvements in speech recognition which were more consistent with their electrode difference limens. Patient 5's overall speech perception performance was poorer than that of the other patients both pre- and post-training and this was reasonably consistent with her wider apical difference limen (Table 3 and Figs. 1 and 6).

DISCUSSION

Four of the five patients showed significant improvement on at least one of the assessments after training. Only two of the patients, however, demonstrated improvement across a number of tasks, ranging from minimal vowel pair tasks to closed-set tasks with a number of alternatives. It is of course possible that patients may have shown greater gains after more extensive training. The training program was short because of time restrictions in withdrawing the children from classroom work. Walden et al. (1981) found, however, that adult hearing aid users benefited from only 7 hr of consonant recognition training. The training in the current study, although short, was very focused.

Natural versus Synthetic Speech Recognition

Synthetic vowel recognition for the six short vowels after training, ranged from 38 to 85%, with a mean of 59%. Blamey and Clark (1990) reported a similar range (36 to 80%) and mean performance (62%) for the same six short vowels by four postlinguistically deafened adults. For the patients in the present study there was generally little difference across time between performance on the natural vowel task versus the synthetic vowel task. Because the training used natural voice it was possible that training may have inadvertently improved patients' ability to use other cues such as intensity and F0 in natural vowel perception. This did not seem to be the case because the changes in natural vowel perception over time did not exceed the changes in synthetic vowel perception. In keeping with the findings of Blamey and Clark (1990), one would also have anticipated higher absolute scores for the naturally spoken vowels which have intensity, F0 and

durational differences and differences in the rate and extent of formant transitions as well as place pitch cues. Such a difference generally did not occur. Perhaps such cues were less conspicuous in this particular recording. It is also likely that the patients were not optimally utilizing the suprasegmental information.

Generalization

For one of the patients (Patient 3), gains in vowel perception generalized to a monosyllabic word task in which consonants and/or vowels differed. It is possible that the highly significant gain on the 12-alternative word task reflects an overall improvement in the place-pitch ability of this child for consonants and vowels that were not trained, as well as for the vowels trained. Alcantara, Whitford, Blamey, Cowan, and Clark (1990) in a training study with profoundly hearing-impaired children using a multichannel electrotactile aid (Tickle Talker), reported some transfer of skills acquired to untrained stimuli. Their study used a more intricate design in which a particular feature was being trained while pretraining scores were collected on a second speech feature. They did not find transfer of training from a feature trained to a feature that had not been trained. In contrast, they did find evidence of generalization for features when the same feature was presented in an untrained context. In this sense it could be argued that in the present study some generalization of training took place for all patients who showed any improvement, because the test items presented the vowels in untrained contexts.

Retention

There was some attempt to consider retention of skills which had shown improvement. In all cases significant gains made by patients were found to be retained 3 wk after the completion of the training program. Alcantara, Whitford, Blamey, Cowan, and Clark (1990) also found that perceptual skills at a speech feature level were retained after the removal of training.

Relationship between Vowel Recognition and Electrode Discrimination

Electrode discrimination was measured using an adaptive procedure which expedites psychophysical data collection with children. With the exception of Patient 5, the difference limens obtained ranged from 1 to 3 electrodes. The difference limens found in this study were not dissimilar to those obtained in a recent study by Busby and Clark (1996) in which an adaptive procedure was used to obtain difference

limens in six early-deafened implant patients aged 5 yr 2 mo to 17 yr 7 mo at the time of surgery. Difference limens ranged from one to four electrodes from the reference electrode for most patients, but were considerably poorer for one patient who was implanted at a later age and had the longest duration of deafness.

Patient 5's speech recognition performance was consistently poorer than that of the other patients. Based on Figure 1 and Table 3, Patient 5 would be expected to have some difficulty recognizing /had/hood/, /had/hud/, and /hood/hod/ because of the larger apical electrode difference limen. Nevertheless, Patient 5's recognition of /had/hood/ was consistently and significantly above chance (Fig. 6). It is possible that the F1 formant contrast between electrodes 16 and 19 is salient here. A difference limen for electrode 19 was not measured. Similarly this patient's ability to discriminate /head/hud/ could be partly explained by the possibility of electrode 19 sounding different. More specific predictions about vowel recognition performance based on electrode discrimination (Table 3) and vowel electrode maps (Fig. 1) could only have been made if electrode difference limens had been obtained for every electrode. This was not a viable option in this training study.

Vowel perception performance before training for Patients 3 and 4 was not consistent with the measured electrode discrimination ability (see Figs. 1, 4, and 5 and Table 3). For example, Patient 3 could not differentiate between the vowel pair /had/hod/ whose electrode separation was seven electrodes, despite difference limens of one to three electrodes. As discussed in the Introduction, it should not be assumed that a patient with small difference limens will show good vowel perception, even at a minimal pair level of assessment. It was predicted, however, that these patients should have the potential to improve with training, given their reasonable electrode discrimination. Specific hierarchical training did appear to help Patients 3 and 4 to fulfill their potential to optimally utilize formant information in vowel recognition.

One would also have expected training to have benefited Patients 1 and 2 whose electrode difference limens were reasonably small. Specific training did not, however, help Patients 1 and 2 to substantially improve their vowel perception. Other factors must be accounting for their poorer vowel perception performance. It is possible that some areas of the electrode array have poorer channel independence and even pitch reversals. For example, for Patient 2, performance for the vowel pair /head/hud/ was not significantly above chance, despite the overall electrode separation being seven electrodes, well in

excess of the patient's difference limens (Fig. 3). The electrode discrimination between adjacent electrodes in the region from electrode 10 to electrode 16 (the F2 separation for head/hud) or between electrodes 21 and 17 (the F1 separation for this pair) may be poorer and include pitch reversals. This explanation would still be compatible with the difference limen of one to two electrodes for the reference electrode 18. A substantial reversal in pitch for electrodes in the middle of the array using common ground stimulation was observed for three postlinguistically deafened adults (Busby, Whitford, Blamey, Richardson, & Clark, 1994). Nelson, Van Tasell, Schroder, Soli, and Levine (1995) reported instances of localized pitch reversals in some adult users of the Nucleus device who were mapped in bipolar modes of stimulation. Similarly, Busby et al. (1994) observed localized pitch reversals for some patients using common ground stimulation.

It is unlikely that Patient 1's greater difficulty with the vowel pairs, /hid/hod/ and /head/hood/ which had relatively wide electrode separation, could be attributed to localized regions of poorer channel independence and/or pitch reversals. Unpublished data (Busby, Reference Note 1) revealed no evidence of pitch reversals or localized areas of poor channel independence in common ground mode of stimulation for this patient.

Other factors must be accounting for the poorer speech perception of Patient 1. An interesting finding was the excellent vowel perception performance for this patient for all pairs except /hud/hod/, when the older F0F2 processing strategy was used. In this strategy only one place of stimulation would be stimulated at a time for each of the synthetic vowels; a situation more akin to the psychophysical task, in which the patient listens to only one electrode at a time. The poorer score for /hud/hod/ was to be expected because the F2 electrode separation is only two electrodes. One possible contributing factor in explaining the better overall results with the F0F2 strategy is the absence of electrode interactions which may arise from overlapping regions of neural excitation in the cochlea (Shannon, 1983; Tong & Clark, 1986). Another possibility is that this patient who had a long duration of deafness before implantation, may have difficulty in centrally processing multiple electrode information. The improvement for this patient is not unique because previous studies have reported better speech perception results on certain closed-set assessments for a few patients using the F0F2 strategy (Blamey & Clark, 1990; Tye-Murray et al., 1990a). No improvements occurred with the F0F2 strategy for the other four patients in the present study.

Scores for the 6-alternative short vowel tasks for

Patient 1 did not, however, improve with the F0F2 strategy. This is not incompatible with the minimal pair results. The F0F2 strategy may allow better discrimination of the six short vowels for Patient 1, but experience over time with this strategy would probably be needed for long-term memory coding and improvement on the 6-alternative short vowel tasks to occur. In contrast, in the minimal pair task, the patient only has to hold the labels in a short-term memory recall. The procedure used in this study allowed the patients to learn the labels for the particular vowel sounds before the commencement of the test items because practice items were provided to refamiliarize the patients with the unusual sound of the synthetic stimuli.

Another factor that may be contributing to the lack of improvement after training for Patients 1 and 5, is the longer duration of profound deafness before implantation. Research has suggested that children implanted at an earlier age with a short duration of deafness will benefit more from the implant than children with a longer duration of deafness (Gantz et al., 1994; Staller, Dowell, Beiter, & Brimacombe, 1991; Waltzman et al., 1994). It could be argued that those patients with a shorter duration of deafness are more likely to improve after training intervention. In this study Patients 1 and 5, with the greatest duration of deafness (13 to 14 yr), showed minimal to no improvement with training. It is suggested that there is a "critical-period" for learning in the auditory system and that the system must be stimulated before a certain age to achieve significant gains in speech perception. This critical age for plasticity, however, is not known. Both these patients had a well established phonological code using lipreading and kinesthetic feedback, which was effective for their communicative needs. It is possible that these patients were less able to integrate the auditory information provided by the implant than the younger patients, who are still in the process of developing a phonological code.

The patient with the least duration of deafness (Patient 2), however, also showed minimal gain. The cognitive processing problems reported for this patient may restrict the potential for learning to use the information coded by the implant. Substantial gains in vowel perception were made by the two children whose duration of profound deafness was 6 to 7 yr. This finding is compatible with the study by Gantz et al. (1994) in which prelingually deafened children up to 13 yr of age obtained substantial speech perception information from the Nucleus multichannel cochlear implant.

Duration of implant use may be an influential factor in helping to interpret results for Patients 1 and 2. In contrast to the other patients they had

extensive implant experience and habilitation. It is possible that perceptual skills begin to plateau after many years of implant use. It has been reported, however, that children can show gains in speech perception up to at least 5 yr after implantation (Gantz et al., 1994). Gains in perception after 5 yr implant use have rarely been documented but this is simply because they have not been measured over longer periods of time.

CONCLUSIONS

The lack of substantial progress in speech perception after implantation for some congenitally deafened patients is of concern. Can these patients learn to use place-pitch cues in vowel perception after specific training? Out of a group of three children, one adolescent, and one adult, two children revealed significant gains in synthetic vowel perception on a variety of assessments after approximately 10 hr of training. Their speech perception performance was more consistent with electrode position discrimination after training. For one of these children the gains on minimal pair tasks generalized to a meaningful, word recognition task. The poor performance of the adolescent could be partly explained by a wide electrode difference limen in the apical region. Perhaps an alternative means of coding speech information should be considered for this patient, with emphasis on temporal, amplitude information rather than coding formant frequencies as electrode position. The performance of the remaining patients was not associated with poor electrode discrimination.

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