Journal of Speech and Hearing Research, Volume 27, 596–604, December 1984

INITIAL IOWA RESULTS WITH THE MULTICHANNEL COCHLEAR IMPLANT FROM MELBOURNE

RICHARD S. TYLER MARY W. LOWDER STEVEN R. OTTO
JOHN P. PREECE BRUCE J. GANTZ BRIAN F. McCABE
University of Iowa, Iowa City

Two subjects who use the Melbourne multichannel cochlear implant were studied. Live-voice word, consonant, and vowel recognition tests, and a speech-tracking task were administered at regular intervals during the first 90 days after implantation. Results indicated 30–50% correct recognition of vowels (given 9 alternatives) and about 30–60% correct recognition of consonants (given 12 alternatives). Speech tracking showed from two to three times faster rates with the implant and vision compared to a vision-alone condition. After 3–4 months of implant experience, a number of recorded tests from the Minimal Auditory Capabilities battery and the Iowa Cochlear-Implant tests were then administered. These results indicated about 80% recognition of everyday sounds in a five-choice closed-set condition and about 50% recognition of everyday sounds in an open-set condition. The subjects were 50% correct at identifying the accented words in a sentence and about 50% correct at determining the number of syllables in a word. One subject was unable to recognize a sentence as a statement or a question. Background noise (+10 dB S/N) reduced their performance on a four-choice spondee test to chance. Both subjects were able to identify a sound as either a voice or a modulated noise at 95% correct, and both could recognize speaker sex at 95% correct. Neither could discriminate whether two (successive) sentences were spoken by the same speaker or by two different speakers. Remarkably, one subject identified 45% and the other 85% of the words in sentences that were preceded by a contextual picture using sound alone. One subject identified 13% of the words in sentences in sound alone even without contextual information.

Although experimental work is just beginning, it is likely that within the next few years cochlear implants will become a viable rehabilitative strategy for profoundly, postlingually hearing-impaired adults. Unfortunately, the potential benefit of these implants is unclear. This is partially because so few implanted subjects have been evaluated and partially because the reported test procedures and results often were anecdotal.

We have recently implanted the first two subjects in the U.S.A. with the multichannel cochlear implant developed in Melbourne, Australia (Tong et al., 1981). This multichannel device has many potential advantages over single-channel devices currently in use. Single-channel devices are inherently limited because the different frequency components of speech cannot stimulate different places along the basilar membrane. Presumably the separate representations of different frequency regions could facilitate detection of formant locations necessary for the perception of speech. The Melbourne multichannel implant has the ability to stimulate different places along the cochlea, depending upon the spectral composition of speech. The speech processor of the implant determines the frequency region containing the dominant energy between 800 and 4000 Hz. For speech stimuli this usually corresponds to the frequency of the second formant (F_2). The frequency of this dominant peak determines the electrode to be stimulated. The higher the frequency, the more basal is the stimulated electrode (see also Description of the Processing, in the Method section).

Nearly all the reports from the Melbourne group have described results from the same two subjects (see Millar, Tong, & Clark, 1984, for a recent review). Martin, Tong, and Clark (1981) used a speech-tracking procedure (De-Filippo & Scott, 1978), in which subjects had to repeat verbatim passages of live-voice connected discourse. Both subjects had higher scores using the implant and lipreading together than using lipreading alone. Clark, Tong, and Martin (1981) reported that these two subjects recognized 14% and 8% of the test words using electrical stimulation alone for recordings of the CID sentences. Lipreading scores of 14% and 34% on the CID sentences were increased to 68% and 98% with the addition of electrical stimulation. It is noteworthy that live-voice presentation in the sound-alone condition resulted in higher scores than recorded presentations. The subjects were also tested with live-voice presentations of eight consonants in a vowel/consonant/vowel (/aCa/) context (Clark, Tong, Dowell, et al., 1981). The average scores were 37% for sound alone, 36% for vision alone, and 62% for sound plus vision. An analysis of the errors indicated that the features of voicing and manner (Miller & Nicely, 1955) were being recognized. Place information, which should be conveyed to a large extent by second formant frequency, was not detected as well by the subjects. Dowell et al. (1982) expanded on the consonant confusion study to include 12 consonants, presenting results from one of the two subjects. Live-voice presentations by both female and male talkers were used. The results pooled across speakers showed scores of 30% for vision, 48% for sound alone, and 70% for sound plus vision. Feature analysis suggested that the features of place and nasality were not very well perceived (25% information transfer) in sound alone.

Tong et al. (1981) presented live-voice results on several speech and audiovisual tests for one of these subjects. On a 16-item, closed-set spondee recognition test, the

0022-4685/84/2704-0596$01.00/0

subject scored 70% for a familiar female talker and 60% for a male talker. The subject also scored about 10% on the CID sentences (Silverman & Hirsh, 1955) presented by sound alone. On a number of audiovisual tests the improvement of the sound-plus-vision compared to vision ranged from 3% to 70%, depending upon the test and the speaker. On a 10-item closed-set environmental sounds test, the subject scored 30% correct.

Clark, Tong, and Dowell (1983) reported that the two subjects scored 82% and 71% correct on vowel recognition with sound alone from a set of six vowels (in the /hVd/ context). They also noted that the subjects were able to respond better than chance on several prosody tests, and their average scores on monosyllabic word lists (Boothroyd, 1968) were 20% (phonemic score) and 5% (word score) for sound alone.

Our intent here was to evaluate two additional subjects from the U.S.A. using the Melbourne multichannel implant. We wished to determine if our subjects benefited from a multichannel cochlear implant. Specifically, we wished to determine whether the Melbourne implant assisted in the recognition of everyday sounds, prosody, and speech, and whether it augmented lipreading. We further attempted to establish whether it was providing information about the second formant frequency.

METHOD

Subjects

Subject M1, 45 years old and a welder, had a profound congenital hearing loss in his right ear. He used a hearing aid in his left ear most of his life. He recently had a sudden decrease of hearing on the left, and hearing aid use caused vertigo and nausea. Thresholds in the right (implanted) ear were 90 dB HL at 250 Hz, 95 dB HL at 500 Hz, 110 dB HL at 750 Hz, and no response (>110 dB HL) between 1000 and 8000 Hz. Thresholds in the left ear were 90 dB HL at 250 Hz, 95 dB HL at 500 Hz, 105 dB HL at 1000 Hz, 105 dB HL at 2000 Hz, 110 dB HL at 4000 Hz, and no response at 8000 Hz. Aided speech detection threshold in the left ear was 60 dB HL; therefore, the subject was unable to hear our test materials, which were presented at about 65 dB SPL (55 dB HL). Aided speech detection threshold in the right ear was 50 dB HL. He was unable to complete any preimplant tests, even when presented at levels greater than 60 dB HL, because he would become vertiginous or nauseated after 10–15 min of hearing-aid use. He received his implant in June 1983. Subject M1 had adjusted to his implant successfully and had been using it for about 3 months at the time of the tests reported here. He has not noted any vertigo or nausea from implant use.

Subject M2 is 33 years old and a computer programmer at an insurance company. He became hearing impaired at about age 23 as a result of Cogan's disease. This syndrome is characterized by corneal inflammation, vertigo, and tinnitus, followed by progressive sensorineural hearing loss. He had been profoundly hearing impaired for 8 years before implantation. Preimplant thresholds in the left (implanted) ear were 90 dB HL at 250 Hz, 110 dB HL at 500 Hz, and no response (>110 dB HL) between 1000 and 8000 Hz. Thresholds in the right ear were no response (>90 dB HL) at 250 Hz, 100 dB HL at 500 Hz, 90 dB HL at 1000 Hz, 85 dB HL at 2000 Hz, and no response (>110 dB HL) between 3000 and 8000 Hz. His aided speech detection threshold was 80 dB HL in the left ear and 50 dB HL in the right ear. He could not hear our test material when aided in the left ear. With the right ear aided, the tests were only just audible to him at 65 dB SPL. At a higher presentation level of 80 dB SPL he got 0% correct on the W-22 word list (Hirsh et al., 1952), and was at chance for the MAC Question/Statement, Noise/Voice, and Accent tests (Minimal Auditory Capabilities battery, Owens, Kessler, Telleen, & Schubert, 1981). He was implanted in the left ear in May 1983. Initially he wore both the implant and the hearing aid, but said that the sound from the implant dominated his perception. He reported that he continued to wear his hearing aid in the right ear so that he could tell if his external coil moved off center with respect to the internal coil. If this occurred, the sound processed by his left implanted ear would no longer dominate. After 2 months of implant use he stopped wearing his hearing aid. He had been using his cochlear implant for 4 months at the time of the most recent test battery administration.

Soundfield audiograms obtained after 3–4 months of implant use at the time of the MAC and Iowa Cochlear-Implant tests (Tyler, Preece, & Lowder, 1983) are shown in Table 1. The ASHA (1978) guidelines were used to obtain thresholds. Speech detection thresholds were obtained live voice for a male speaker for M1 and a female speaker for M2. The gain setting chosen was the one used by the subject in a quiet listening situation.

Description of the Processing

The Melbourne (Nucleus Ltd., Sydney, Australia) implant consists of 22 electrodes that are stimulated as bipolar pairs (Patrick et al., 1984). In the two subjects described here, the electrode pairs (active and ground) were separated by one other electrode. Thus, electrodes 1 and 3 were a pair, 2 and 4, 3 and 5, 4 and 6, 20 and 22, resulting in 20 channels. The speech processor stimulates only one of these channels at a time. The channel that is selected is determined by the dominant peak in the region between 800 and 4000 Hz. For a speech stimulus this will usually approximate the second formant frequency. Low-frequency peaks in the input to the processor result in stimulation of an apical channel, and energy in the high-frequency region results in stimulation of a basal channel. A biphasic pulse train is presented at the selected channel with a rate intended to reflect the periodicity in the waveform at the input to the processor. For a voiced speech stimulus this will reflect the voicing or fundamental frequency. For unvoiced sounds the pulse rate varies aperiodically around 125 Hz.

TABLE 1. Soundfield audiograms obtained after 3–4 months of implant use.

Subject	*Speech detection threshold*	*Signal frequency (Hz)*									
		125	*250*	*500*	*1000*	*2000*	*3000*	*4000*	*6000*	*8000*
M1	30	>60	55	60	45	40	40	35	45	55
M2	45	>60	70	55	45	55	45	40	45	60

Note. Warble tones: 10% frequency modulation at five per s in dB HL obtained with the subjects wearing the implant.

Setting the Device

About 3–4 weeks after implantation, as soon as the surgical site had healed sufficiently, the subject was brought in to adjust the speech processor. A Sanyo MBC 1000 computer, a speech-processor interface, and specialized software (developed by Nucleus Ltd.) were used to conduct some psychophysical tests that were used to adjust the processor, record the subject's responses, and download the appropriate coding parameters into the Erasable Programmable Read Only Memory (EPROM) of the unit. The protocol we followed for setting the device was provided to us by Nucleus Ltd. First, biphasic pulses were delivered to a single electrode (usually the most apical of the 20 pairs) via a hand-held external coil. The subject was questioned regarding sound perceptions while the coil was repositioned over the site of the internal coil until the subject reported the loudest perception of sound. This determined the placement for the external coil.

The next step was to measure threshold and maximum comfortable loudness (maxCL) for each electrode using a 125-Hz stimulus of biphasic pulses. The instructions for the maxCL were to adjust the stimulus to the loudest level which was still comfortable. The subject set these levels by the method of adjustment. This was repeated for each electrode pair. Then, a sweep was made through the electrode pairs by stimulating each successively, and the subject was asked if the pitch perception changed in an orderly fashion and if any sound was louder or softer than others. The subjects reported pitch sensations that are consistent with the sharp-to-dull order associated with basal-to-apical stimulation reported by Tong, Blamey, Dowell, and Clark (1983). Some of the electrodes that were stimulated first produced a softer loudness than other electrodes, and these had to be reset to a new maxCL. The sweep procedure was repeated until all the electrodes sounded about equally loud. The threshold and maxCL data were used to program a "map" onto an EPROM. This map provided the algorithm for selection of electrodes for stimulation and current levels delivered to the subject's internal coil, which depend on the input signal amplitude and frequency. It also ensured that no sound was presented to the subject at levels exceeding his maxCLs. The subject took the processor home overnight after receiving instruction on operation and maintenance.

Initial 10 Sessions

During the first 10 postoperative sessions (spaced about one week apart) the subject's processor was occasionally readjusted to allow for changes in threshold and maxCL. Usually these adjustments were to increase the maxCL, which would increase the dynamic range. Most of these adjustments were made during the first three or four sessions. Activities during all 10 sessions also included structured use of the telephone, use of assistive devices for the deaf, and some group discussions with other implant users. Throughout these 10 sessions, the audiologists (a male for M1 and a female for M2) working with each subject were required (by Nucleus Ltd.) to perform live-voice tests defined by a clinical trial protocol. The two audiologists worked with and tested each subject to accommodate our own clinic scheduling. We note that Dowell et al. (1982) used both a female and male speaker for the live-voice testing of their single subject. They felt the results obtained from the two speakers were sufficiently similar to justify combining results for their information transfer analysis. The audiologists presented the materials at a normal conversation level, and the subject was seated about 1 m from the audiologist. The subjects set their devices as they would when listening to normal conversation in a quiet room. These tests included word identification, vowel and consonant recognition, and speech tracking and were presumably designed to monitor performance over the first weeks of implant usage.

Word identification. During each session, 10 consonant/vowel/consonant (CVC) words from the lists developed by Boothroyd (1968) were presented live voice, sound alone (open-set). The subject could request that the words be repeated. A score was recorded for the number of phonemes and the number of whole words repeated correctly. No feedback was provided. To get some idea of chance performance, we asked five people to write down any 10 CVC words. Each list of 10 words was then compared against the 10 word lists used in the study. These responses produced an average score of 5% correct phonemes and 0% correct words.

Vowel confusions. Three or four (depending on time constraints) randomized presentations of nine vowels (in the context *heard, had, hid, hawed, who'd, head, hud, heed, hood*) were presented to the subject via live voice during sessions 1, 3, 5, 7, and 9. The subject could request that the word be repeated. This list was presented in sound, vision, and sound-plus-vision conditions. The subject was provided with a list of the options for reference and feedback was not provided.

Consonant confusions. Twelve consonants presented in a /aCa/ format were read to the subject in exactly the same manner as the vowel confusions. The subject could request that the item be repeated. Twelve alternatives were provided without feedback. Three or four (depending on time constraints) randomized presentations were administered during sessions 2, 4, 6, 8, and 10.

Speech tracking. The subject was asked to repeat exactly what a speaker read from a simple novel (*Irish Red*, by J. Kjelgaard. Scholastic Book Services, New York, 1957). If the subject was unable to repeat the words exactly, the speaker resorted to a number of hierarchical strategies involving repeating, shortening the message, rephrasing, and eventually phonemically breaking down each word if necessary (DeFilippo & Scott, 1978) until the exact repetition was obtained. A vowel and consonant classification chart was provided for the subject on which he could point to the class of phoneme he was trying to identify. The speaker could then redirect the tracker's attention to the proper class of sounds by saying, for example, "It has voicing." The subject tracked for 10 min wearing the speech processor using lipreading and 10 min using lipreading alone. The order of these conditions was alternated each session. The number of words the subject could repeat per minute was recorded for both conditions. Although we did not knowingly attempt to bias the results, the speaker knew the listening condition (processor plus lipreading or lipreading alone) of the subject.

Administration of MAC and Iowa Tests

We also administered (recorded) portions of the Minimal Auditory Capabilities battery (MAC) (Owens et al., 1981) and the Iowa Cochlear Implant Test battery (Tyler et al., 1983) after the subjects had 3–4 months of experience using their cochlear implants. The Iowa tests and their administration are described in Tyler et al. (in press). The tests were presented at about 65 dB SPL in a sound-treated room. All tests were given once, with the exception that the Noise/Voice and Question/Statement tests were repeated twice (different randomizations) to improve the accuracy of statistical analysis.

RESULTS

Word Identification

The results obtained during the first 10 sessions for M1 (left panels) and M2 (right panels) are summarized in Figure 1. Neither subject recognized more than 2 of the 10 single-syllable words with sound alone at any test session. Scoring at the phoneme level appears to increase from about 20 to 40% correct with experience.

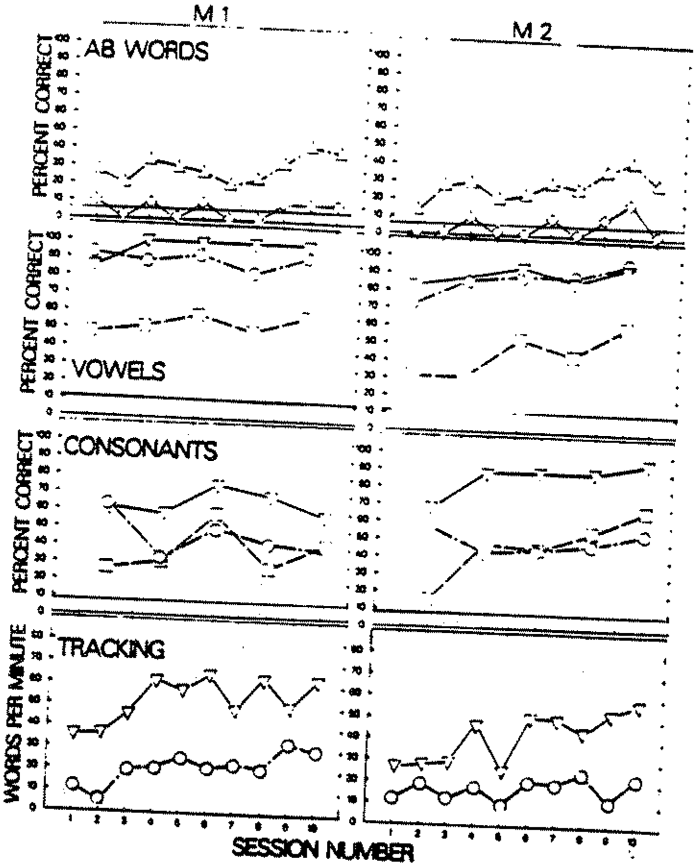

FIGURE 1. Results for subjects M1 (left panels) and M2 (right panels) on the 10-item closed-set Arthur Boothroyd word-recognition test (upper), the 9-item vowel test (second panel), the 12-item consonant test (third panel), and the speech-tracking procedures (lower panel). For the Boothroyd word test, diamonds represent word score, and triangles represent phoneme score, both presented with sound alone. In the other three pairs of panels, the symbols represent sound (squares), vision (circles) and sound-plus-vision (diamonds). Horizontal lines represent a chance level of performance.

Vowel Tests

The next panels in Figure 1 include their scores on the nine-item closed-set vowel test. Using sound alone, M1's scores increased from about 50 to 60%, whereas M2's scores increased from about 30 to 60% across the 10 sessions. Vowels were typically more easily lipread than consonants (Berger, 1972), and scores for both subjects were high with vision alone. M2 showed an improvement in his lipreading skills with time. The high scores on the vision condition restricted the gain that could be observed in sound plus vision.

Figure 2 shows the vowel confusion matrix obtained in the sound-alone condition, averaged across sessions. M1 had difficulty recognizing /ɛ/, /ɝ/, /ʌ/, and /u/. The /ɝ/ was perceived as an /ɔ/. M2 had difficulty recognizing /ɝ/, /ʌ/, /ʊ/, and /u/. Again the /ɝ/ was perceived as an /ɔ/, and additionally, the /u/ was perceived as an /ʊ/. The data of Peterson and Barney (1952) suggest little overlap between the range of second formant frequencies for /ɝ/ and response

stimulus	i	ɪ	ɛ	æ	ɝ	ʌ	ʊ	u	ɔ
i	16								
ɪ	1	14					1		
ɛ		1	5	5	2	1	2		
æ	1			9	1		1	1	3
ɝ					3	1			12
ʌ				4	5	6			1
ʊ					1	4	8		3
u	1			2	5	3	1	1	3
ɔ				1					15

response

stimulus	i	ɪ	ɛ	æ	ɝ	ʌ	ʊ	u	ɔ
i	18	1			1				
ɪ	4	9	3	2	1		1		
ɛ	1	5	8	4	2				
æ		2	3	10	3	1			1
ɝ					4	2			14
ʌ		1	1	4	2	5	3		4
ʊ		2	1	5	3	2	6		1
u	2	2	1	2	1	1	8	2	1
ɔ					2		3		15

FIGURE 2. Live-voice vowel confusions for M1 (top) and M2 (bottom) for sound-alone presentation. The vowels were presented in the /hVd/ context. The speaker for M1 was a male, and 16 replications of each stimulus were provided. The speaker for M2 was a female, and 20 replications were provided.

/ɔ/ spoken by men and children. However, the /u/ and /ʊ/ do show a large overlap in second formant frequency.

Consonant Tests

The third panels from the top in Figure 1 show the results from the 12-item closed-set consonant test. With sound alone, M1's scores varied around 40%. The scores of M2 increased from 15 to nearly 70% across trials. With vision alone, M1's scores were again variable, and both M1 and M2 scored about 50% correct. An improvement was noted for both subjects in sound-plus-vision compared to vision. For the first session, without any prior experience, this advantage was small. But for later sessions this advantage was about 20% for M1 and 30–40% for M2.

Figure 3 shows the consonant confusion matrices for M1 (top) and M2 (bottom). In each cell, the number of responses are shown for sound (upper left), vision (center), and sound-plus-vision (lower right). Over the 10 sessions, M1 received 16 trials for each consonant. Overall, he scored 35% correct for sound, 44% correct for vision, and 64% correct for sound-plus-vision. M1 scored at least 6 correct of 16 trials in sound-alone conditions in the recognition of /m/, /s/, /z/, /t/, /n/, and /g/. He scored less than four correct for /p/, /b/, /v/, /f/, /d/, and /k/. An increase in at least four correct in sound-plus-vision over vision was seen for /p/, /m/, /t/, /n/, and /g/. M2 scored similarly to M1, with the exception that he had higher scores on /b/, /v/, /f/, /d/, and /k/ in the sound-alone conditions.

Figure 4 shows the results obtained from analyzing these confusion matrices in terms of the information transfer of particular features (Dowell et al., 1982; Miller & Nicely, 1955). Scoring was based on whether a particular feature, as opposed to a particular phoneme, was identified correctly. In an information transfer analysis, chance performance is represented by 0%. The results from M1 showed that, in sound alone, the implant coded about 20% of the information about the place feature, about 70% of the information about nasality and duration; and only about 10% of the information about voicing and affrication. Improvements of at least 20% information transfer in sound-plus-vision compared to vision were seen for the features of duration, affrication, and nasality. The information about nasality in sound-plus-vision, however, was similar to the score in the sound-alone condition.

In sound alone, the results from M2 showed that the implant provided about 20 to 30% information about all features except voicing, where a 55% information transfer score was achieved. An improvement of almost 20% in information transfer in sound-plus-vision compared to vision was seen for the place feature and an improvement of about 40% was seen for the voicing and nasality features. The nasality results in the sound-plus-vision condition were similar to those in the sound-alone condition.

Speech Tracking

The speech-tracking results are shown in the bottom panel of Figure 1. There was some improvement of scores over time in the vision condition (without the processor). The advantage of sound-plus-vision was consistent across sessions, and was about a constant 30 words per min for M1. M2 showed a small advantage over the first three sessions, but this advantage increased to about 35 words per min by session 10. These results indicated about a

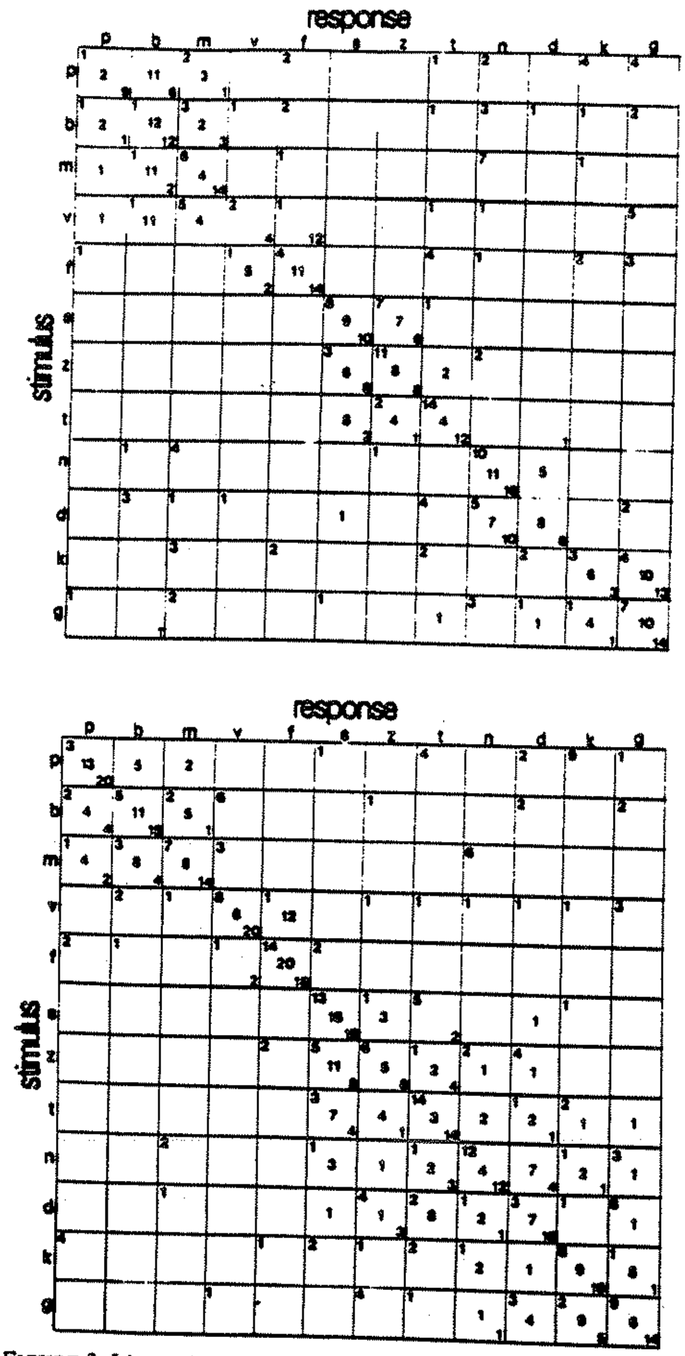

FIGURE 3. Live-voice consonant confusions for M1 (top) and M2 (bottom). In each cell, the upper-left number represents the sound-alone condition, the center number represents the vision-alone condition, and the lower-right number represents the sound-plus-vision condition. The speaker for M1 was a male, and 16 replications of each stimulus were provided. The speaker for M2 was a female, and 20 replications were provided.

two-fold to four-fold increase in tracking performance for sound-plus-vision compared to vision.

MAC and Iowa Tests

The MAC and Iowa tests were performed from 3 to 4 months after initial connection of the implant. We wished to determine if the test scores were statistically higher than those that would be expected from guessing (chance). Given the likelihood of a correct response by chance (e.g., .20 on a five-alternative trial) and the number of items on a test, and assuming a normal distribution of scores that would be obtained by someone guessing, we can determine Z scores and use the standard normal distribution to determine the level of significance (Owens et al., 1981).

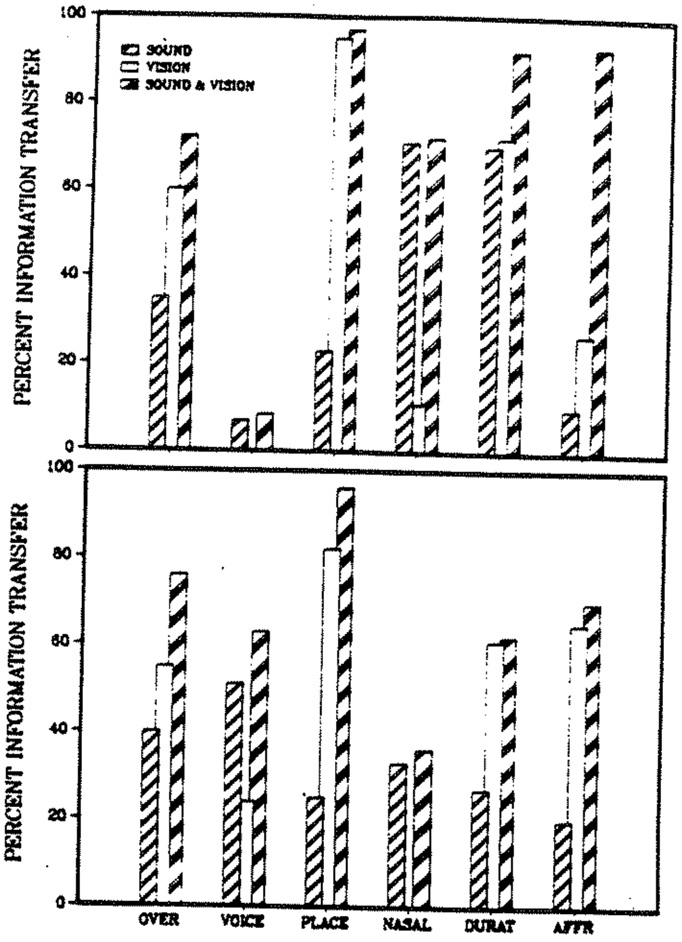

FIGURE 4. Information transfer analysis (Miller & Nicely, 1955) for consonant confusion data presented in sound, vision, and sound-plus-vision conditions. Scores are shown for the overall (OVER) features correct, and for the voice, place, nasal, duration (DURAT) and affrication (AFFR) features. Results for M1 (top) and M2 (bottom) are shown.

The results for the Everyday Sound and Prosody tests are shown in Table 2. The two subjects could identify the everyday sounds at about 80% correct in a closed-set (five choice) and at about 50% correct in an open-set situation. Only M2 scored above chance at reporting whether a sentence was a question or a statement, but both scored above chance in determining the accented word in a sentence and the number of syllables in a word.

Table 3 contains the results on tests using spondee words. Both subjects scored above chance on spondee recognition (no alternatives provided) and four-choice spondee recognition. In the noise background (+10 dB

TABLE 2. Results for the everyday sound tests and prosody tests.

Subject	*Everyday sound* Closed-set %	Open-set %	*Prosody* Question/ Statement %	Accent %	# Syllables %
M1	75*	50*	42.5	50*	71*
M2	85*	45*	72.5*	50*	41.7*
Chance	20%	0%	50%	20%	25%
# of items	20	20	40	20	24

Note. Here and in the following tables we have identified those values that are significantly higher than would be expected by guessing (* = $p < .05$), suggested by Owens, Kessler, and Schubert (1982). We determine the variance of the distribution that would be expected from guessing by assuming a normal distribution and knowing the likelihood of a correct response by guessing on each trial (.20 for a five-alternative test) and the number of items in the test.

TABLE 4. Results on speech-related tasks.

Subject	Noise/Voice %	Female/Male %	Speaker discrimination Different sentence %
M1	95*	95*	50
M2	95*	95*	65
Chance	50%	50%	50%
# of items	40	20	40

*$p < .05$.

signal-to-noise ratio) neither subject scored above chance.

Table 4 contains the results from speech-related tasks. Both subjects scored 95% correct (a) determining whether a sequence of sounds was a voice or an amplitude-modulated noise and (b) at recognizing speaker sex. In contrast, neither was able to determine if two different sentences were spoken by the same or by different speakers.

Results from the audiovisual tasks in sound (S), vision (V), and sound-plus-vision (S + V) conditions are shown in Table 5. To test for significant differences between V and S + V, we used the binomial model suggested by Thornton and Raffin (1978). In the sentence tests, each word is not independent; therefore, this statistical test will be lenient. In sound alone with contextual information, M1 scored 45% and M2 scored 85% correct recognition of words in sentences. M2 was able to score 13% correct even without contextual information. In a live-voice presentation with a familiar speaker, both subjects recognized about 25% of the words in a sentence. In vision alone note that both subjects were excellent lipreaders. We evaluated the statistical significance of the improvement in lipreading provided by the implant using an arcsine transformation and a binomial model as suggested by Thornton and Raffin. Although scores on the sound-plus-vision condition were always greater than scores on the vision condition, the amount of improvement was restricted by their very high scores with vision alone.

CONCLUSIONS

Our results indicated that these two subjects benefited from receiving a cochlear implant. Before they received their implants, M1 was unable to wear a hearing aid because sounds made him dizzy and nauseated, and M2 was unable to obtain any benefit by use of a conventional hearing aid. Following implantation, both could recognize some environmental sounds, even in an open-set condition. Some prosodic information was provided, as was evident on the Question/Statement, Accent, and Number of Syllables tests. This information should help these subjects parse phrase, word, and syllable boundaries, and assist in their understanding some suprasegmental features of sentences, such as stress and intonation. Both subjects could recognize a voice and decide whether it was a female or male speaker. They had great difficulty in discriminating unfamiliar speakers of the same sex. The recognition of words in isolation was generally very poor. These subjects did not hear speech in the same manner as people with normal hearing. They were able to correctly select some vowels and consonants from the limited amount of information they received. It was very encouraging that both subjects recognized some

TABLE 3. Spondee test results.

Subject	Four-choice %	Four-choice Noise %	Recognition %
M1	60*	20	12*
M2	90*	25	24*
Chance	25%	25%	0%
# of items	20	20	50

*$p < .05$.

TABLE 5. Results from the audiovisual tasks.

	Audiovisual sentence tests								
	Context			*No-context*			*Companion*		
Subject	S %	V %	S+V %	S %	V %	S+V %	S %	V %	S+V %
M1	45*	92*	97	1	89*	94	33*	96*	99
M2	85*	90*	95	13*	88*	93	20*	93*	99+
Chance	0%			0%			0%		
# of items	157			153			135		

*$p < .05$. The + indicates a significant improvement of the S+V over the V condition.

words in the sentence materials. With context, M2 scored 85% with sound alone and even without context, 13% correct. Both subjects scored about 25% correct with a familiar speaker, suggesting the importance of learning individual characteristics of the speaker, such as formant locations for certain sounds and typical syllable and phrase timing patterns. This effect might also suggest that performance will improve over time with experience using the limited cues.

Although we saw only limited improvement in sound-plus-vision compared to vision on the sentence tests, this was due to the high scores obtained in vision alone. Both subjects were excellent lipreaders. The consonant confusion test and the speech-tracking task showed a consistent improvement in lipreading using the implant. In general our findings are in good agreement with those reported by the Melbourne group. Profoundly hearing-impaired adults have improved their communicative abilities in several areas after receiving the Melbourne multichannel cochlear implant. We should note that these results are comparable, but not decisively superior, to those reported by ourselves (Tyler et al., in press) and others (Hochmair-Desoyer, Hochmair, Fischer, & Burian, 1980; Owens, Kessler, & Schubert, 1982) using single-channel implants. However, it is noteworthy that both of our multichannel subjects (both with limited implant experience), demonstrated some open-set speech understanding. Whether the observation of limited speech understanding is exceptional with single-channel implants and common with multichannel implants will require data from more subjects.

It is of interest to examine further some of the consonant features perceived by these subjects in the sound-alone condition. M1 detected few of the voicing features, whereas M2 got over 50% of the information. The voicing feature should be extracted by the device so that voiced sounds will result in periodic pulses, and unvoiced sounds will produce aperiodic pulses. Thus, the perception of voicing will depend on the ability of the device to detect voiced or unvoiced sound, the peripheral auditory system to code precise time intervals, and higher levels to decide on periodicity/aperiodicity. The accuracy of the device in coding the voicing contrast is unknown (cf. Dowell et al., 1982). The larger individual differences in performance on this feature might suggest that "top-down" cognitive processes (on the phonetic level, e.g., the ability to use a variety of cues that could contribute to voicing detection, and on a more global level, e.g., the ability to use word and sentence context to accurately predict distorted phonemes or words) play an important role. If this were so it might be possible to improve M1's performance on the voicing contrast with rehabilitation by focusing on and emphasizing various acoustic cues that contribute to the voicing perception (Summerfield & Haggard, 1977).

Dowell et al. (1982) suggested that the nasality feature might be coded by a lower amplitude F_2 relative to nonnasal sounds. The high performance of M1 suggests that the device is able to preserve the important acoustic parameters that code this feature. Both subjects received some, but limited, information about the affricative feature. The feature is based on the presence of turbulence or friction noise, as in /f, v/ but not in /p, b/. The speech processor should have difficulty coding this, because neither voicing nor F_2 position is a cue.

Both our subjects scored about 25% correct on the place feature. This implant was designed to code second formant frequency (F_2) onto electrode position, F_2 being the predominant cue for the place feature. The psychophysical data provided by Tong et al. (1983) suggest that frequency transitions can be discriminated by these subjects with this coding scheme. What is unclear, however, is how successful the device is in selecting the F_2 frequency. Our results suggested that the multichannel implant is only partially successful in its goal in providing information about F_2.

It is interesting that the features of voicing and nasality can be coded by single-channel cochlear implants (e.g., Tyler et al., in press) or vibrotactile aids. Single-channel devices (Fourcin et al., 1979) designed to code voicing frequency only (with the exclusion of other, possibly confusing, information) may even be better at coding single features than multichannel devices. Both Hochmair-Desoyer et al. (1980) and Owens et al. (1982) have reported exceptional subjects using single-channel cochlear implants, where there appeared to be limited word recognition and evidence for some formant decoding. However, it is unlikely that single-channel implants or single-channel vibrotactile aids have the ability to code F_2. This will likely be necessary to understand free-running speech in sound-alone conditions. The Melbourne device appears to be only partially successful in conveying F_2 information. Further subject experience and training may help these subjects learn to use this new, limited information.

ACKNOWLEDGMENTS

We are grateful to Richard Dowell, Mike Hirshorn, Jim Patrick, Peter Crosby, and Gerry Zimmermann who made helpful comments on the manuscript. Portions of these data were presented at the 1983 American Speech-Language-Hearing Convention in Cincinnati, at the 1983 Second International Symposium on Cochler Implants in Paris, and at the 1983 Symposium on Cochlear Implants in San Francisco.

REFERENCES

AMERICAN SPEECH AND HEARING ASSOCIATION. (1978). Guidelines for manual pure-tone threshold audiometry. *Asha, 20,* 297–301.

BERGER, K. W. (1972). *Speechreading. Principles and methods.* Baltimore: National Educational Press.

BOOTHROYD, A. (1968). Developments in speech audiometry. *Sound, 2,* 3–10.

CLARK, G. M., TONG, Y. C., & DOWELL, R. C. (1983). Clinical results with a multichannel pseudobipolar system. In C. W. Parkins & S. W. Anderson (Eds.), Cochlear Prostheses: An International Symposium. *Annals of the New York Academy of Sciences, 405,* 370–376.

CLARK, G. M., TONG, Y. C., DOWELL, R. C., MARTIN, L. F.,

SELIGMAN, P. M., BUSBY, P. A., & PATRICK, J. F. (1981). A multiple-channel cochlear implant: An evaluation using nonsense syllables. *Annals of Otology, Rhinology, and Laryngology, 90*, 227–230.

CLARK, G. M., TONG, Y. C., & MARTIN, L. F. (1981). A multiple-channel cochlear implant: An evaluation using open-set CID sentences. *Laryngoscope, 91*, 628–634.

DEFILIPPO, C., & SCOTT, B. (1978). A method for training and evaluating ongoing speech. *Journal of the Acoustical Society of America, 63*, 1186–1192.

DOWELL, R. C., MARTIN, L. F. A., TONG, Y. C., CLARK, G. M., SELIGMAN, P. M., & PATRICK, J. F. (1982). A 12-consonant confusion study on a multiple-channel cochlear implant patient. *Journal of Speech and Hearing Research, 25*, 509–516.

FOURCIN, A. J., ROSEN, S. M., MOORE, B. C. J., DOUEK, E. E., CLARKE, G. P., DODSON, H., & BANNISTER, L. H. (1979). External electrical stimulation of the cochlea: Clinical, psychophysical, speech-perceptual and histological findings. *British Journal of Audiology, 13*, 85–107.

HIRSH, I. J., DAVIS, H., SILVERMAN, S. R., REYNOLDS, E. G., ELDERT, E., & BENSON, R. W. (1952). Development of materials for speech audiometry. *Journal of Speech and Hearing Disorders, 17*, 321–337.

HOCHMAIR-DESOYER, I. J., HOCHMAIR, E. S., FISCHER, R. E., & BURIAN, K. (1980). Cochlear prostheses in use: Recent speech comprehension results. *Archives of Otorhinolaryngology, 229*, 81–98.

MARTIN, L. F. A., TONG, Y. C., & CLARK, G. M. (1981). A multiple-channel cochlear implant. Evaluation using speech tracking. *Archives of Otolaryngology, 107*, 157–159.

MILLAR, J. B., TONG, U. C., & CLARK, G. M. (1984). Speech processing for cochlear implant prostheses. *Journal of Speech and Hearing Research, 27*, 280–296.

MILLER, G. A., & NICELY, P. E. (1955). An analysis of perceptual confusions among some English consonants. *Journal of the Acoustical Society of America, 27*, 338–352.

OWENS, E., KESSLER, D. K., & SCHUBERT, E. D. (1982). Interim assessment of candidates for cochlear implants. *Archives of Otolaryngology, 108*, 478–483.

OWENS, E., KESSLER, D. K., TELLEEN, C. C., & SCHUBERT, E. D. (1981). *The Minimal Auditory Capabilities battery*. St. Louis: Auditec.

PATRICK, J. F., CROSBY, P. A., HIRSHORN, M. S., KUZMA, J. A., MONEY, D. K., RIDLER, J., & SELIGMAN, P. M. (1984). *The Australian multi-channel implantable hearing prosthesis*. Manuscript submitted for publication.

PETERSON, G. E., & BARNEY, H. L. (1952). Control methods used in a study of the vowels. *Journal of the Acoustical Society of America, 24*, 175–184.

SILVERMAN, S. R., & HIRSH, I. J. (1955). Problems related to the use of speech in clinical audiometry. *Annals of Otolaryngology, Rhinology, and Laryngology, 64*, 1234–1244.

SUMMERFIELD, A. Q., & HAGGARD, M. (1977). On the dissociation of spectral and temporal cues to the voicing distinction in initial stop consonants. *Journal of the Acoustical Society of America, 62*, 435–448.

THORNTON, A. R., & RAFFIN, M. J. M. (1978). Speech-discrimination scores modeled as a binomial variable. *Journal of Speech and Hearing Research, 21*, 507–518.

TONG, Y. C., BLAMEY, P. J., DOWELL, R. C., & CLARK, G. M. (1983). Psychophysical studies evaluating the feasibility of a speech processing strategy for a multiple-channel cochlear implant. *Journal of the Acoustical Society of America, 74*(1), 73–80.

TONG, Y. C., CLARK, G. M., DOWELL, R. C., MARTIN, L. F. A., SELIGMAN, P. M., & PATRICK, J. F. (1981). A multiple-channel cochlear implant and wearable speech-processor. An audiological evaluation. *Acta Otolaryngologica, 92*, 193–198.

TYLER, R. S., PREECE, J. P., & LOWDER, M. W. (1983). *The Iowa Cochlear-Implant test battery*. Iowa City: Department of Otolaryngology–Head and Neck Surgery, University of Iowa.

TYLER, R. S., GANTZ, B. J., MCCABE, B. F., PREECE, J. P., LOWDER, M. W., & OTTO, S. R. (in press). Initial results with single-channel cochlear implants. *Annals of Otolaryngology*.

Received January 13, 1984
Accepted August 14, 1984

Requests for reprints should be sent to Richard S. Tyler, Department of Otolaryngology–Head and Neck Surgery, University of Iowa Hospitals, Iowa City, IA 52242.