The recognition of vowels differing by a single formant by cochlear-implant subjects

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The ability to recognize synthetic, two-formant vowels with equal duration and similar loudness was measured in five subjects with the Cochlear and five subjects with the Symbion cochlear implants. In one set of test stimuli, vowel pairs differed only in the first-formant frequency ($F1$). In another set, vowel pairs differed only in the second-formant frequency ($F2$). When $F1$ differed, four of five Cochlear subjects and four of five Symbion subjects recognized the vowels significantly above chance. When $F2$ differed, two of five Cochlear subjects and three of five Symbion subjects scored above chance. These results suggest that implanted subjects can utilize both "place" information across different electrodes and "rate" information on a single electrode to derive information about the spectral content of the stimulus.

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INTRODUCTION

High levels of audition-only word recognition have been observed in many cochlear-implant patients (for a review, see Hopkinson *et al.*, 1986). This is remarkable considering that most of these patients were profoundly or totally deaf prior to receiving their implant, and considering the relatively simple signal processing of the implants compared to the elaborate transformations and coding in the normal ear. For example, Dorman *et al.* (1988) studied one subject with the Symbion multichannel cochlear implant (Eddington, 1980) who scored 62% on a monosyllabic word test. Similar high levels of performance have been reported by Dorman *et al.* (1989a), Gantz *et al.* (1988), and Cohen *et al.* (1985) for multichannel implant users. Some subjects with single-channel implants (e.g., Banfai *et al.*, 1984; Hochmair and Hochmair-Desoyer, 1985; Tyler, 1988a,b) can also achieve high levels of word recognition.

Several investigations have been designed to ascertain which speech cues are being utilized by these patients. Many patients with a variety of different cochlear implants appear to use information about periodicity and the speech envelope (e.g., Blamey *et al.*, 1987a; Rosen *et al.*, 1989). This information can assist the recognition of some consonants, particularly in consonant–vowel–consonant contexts with a restricted set of alternatives (Van Tasell *et al.*, 1987). In addition, it seems likely that some of these patients use spectral information and information about the relative levels of the stimulus in different frequency regions (Blamey *et al.*, 1987a; Dorman *et al.*, 1988; Dorman *et al.*, 1989b; Tyler *et al.*, 1989).

Spectral information can be conveyed in at least two different ways. In multichannel cochlear implants, energy at different frequencies can stimulate different electrodes located at a different *place*. As long as the stimulation of each different electrode results in a different percept, this information can be used to indicate the spectral composition of the stimulus. Another way that spectral information can be coded is by the neural firing *rate*. The interpulse interval of neural discharges is inversely related to the frequency of the excitory stimulus. This rate information about the stimulus spectrum can be conveyed by single or multichannel cochlear implants.

The present investigation evaluated how well cochlear-implant subjects recognized synthetic vowels that differed only in their spectral composition. Two sets of vowel pairs were synthesized. In one set, each pair of response alternatives differed only in the first formant ($F1$). In the second set, each pair differed only in the second formant ($F2$). The vowels were presented individually, and the subjects were required to select one of the vowels from the appropriate vowel pair. Performance above chance suggests that spectral information is being used by these implant subjects. Subjects using two different multichannel implants, the 4-channel monopolar Symbion implant (Eddington, 1980), whereby analog waveforms are presented simultaneously, and the 21-channel bipolar Cochlear implant (Blamey *et al.*, 1987b), whereby pulsatile waveforms are presented nonsimultaneously, were evaluated.

I. METHOD

A. Subjects

Ten postlingually deafened adults served as subjects. Five used the Cochlear implant and five used the Symbion implant. Each subject had at least 6 months of experience with his/her device. Preimplant audiograms in the test ear showed no response at octave frequencies between 250 and

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8000 Hz for subjects IN1, IN2, IN3, M8, IS1, IS4, and IS3. Subject IN5 had thresholds of 105 dB HL at 500 Hz, 100 dB HL at 1000 Hz, and 105 dB HL at 2000 Hz. Subject IS2 had thresholds of 90 dB HL at 250 Hz, 110 dB HL at 500 Hz, 100 dB HL at 1000, 2000, and 4000 Hz, and 90 dB HL at 8000 Hz. Subject CS1 had a threshold of 115 dB HL at 1000 Hz with no measurable hearing reported at the other test frequencies.

The patients' scores on word recognition in unfamiliar sentences (Tyler *et al.*, 1986) were: M8 = 16%, IN1 = 21%, IN2 = 59%, IN3 = 36%, IN5 = 11%, IS1 = 0%, IS2 = 46%, IS3 = 16%, IS4 = 0%, and CS1 = 88% words correct.

B. Devices

The cochlear implant typically uses 21 bipolar channels that are stimulated nonsimultaneously with current pulses. A feature-extraction scheme codes the fundamental frequency as pulse rate, the speech amplitude as the pulse height, and the first and second formants as the particular low- or high-frequency electrode stimulated. Unvoiced sounds are transformed as a random pulse rate that averages about 110 Hz. Filters with center frequencies less than 1000 Hz were assigned to the $F1$ electrode, whereas filters greater than 1000 Hz were assigned to the $F2$ electrode. Four of the subjects (IN1, IN2, IN3, M8) and five channels assigned to $F1$. These were 280–328 Hz, 329–438 Hz, 439–579 Hz, 580–752 Hz, and 753–1003 Hz. Subject IN5 had seven channels assigned to $F1$; 280–407 Hz, 408–501 Hz, 502–595 Hz, 596–705 Hz, 706–799 Hz, 800–893 Hz, and 894–1003 Hz.

Four of the subjects, IN1, IN2, and IN3, had 15 electrodes assigned to $F2$; 1004–1097 Hz, 1098–1207 Hz, 1208–1317 Hz, 1318–1442 Hz, 1443–1583 Hz, 1584–1740 Hz, 1741–1913 Hz, 1914–2101 Hz, 2102–2289 Hz, 2290–2524 Hz, 2525–2760 Hz, 2761–3026 Hz, 3027–3324 Hz, 3325–3638 Hz, and 3639–4000 Hz. Subject IN5 had 13 channels assigned to $F2$; 1004–1097 Hz, 1098–1223 Hz, 1224–1348 Hz, 1349–1489 Hz, 1349–1489 Hz, 1490–1630 Hz, 1631–1803 Hz, 1804–1991 Hz, 1992–2195 Hz, 2196–2430 Hz, 2431–2681 Hz, 2682–2964 Hz, 2965–3262 Hz, and 3263–4000 Hz. Subject IN2 had 13 channels assigned to $F2$; 1004–1113 Hz, 1114–1223 Hz, 1224–1332 Hz, 1333–1474 Hz, 1475–1630 Hz, 1631–1787 Hz, 1788–1975 Hz, 1976–2179 Hz, 2180–2399 Hz, 2400–2634 Hz, 2635–2901 Hz, 2902–3199 Hz, and 3200–4000 Hz.

The Symbion implant has a maximum of four monopolar channels that are stimulated simultaneously with analog waveforms. Incoming signals are filtered into four channels (bandwidths of 100–700, 700–1500, 1500–2500, and 2500–7000 Hz). The output of each filter stimulates one of the four electrodes.

C. Stimuli

Two sets of vowel pairs were synthesized using a parallel synthesizer (Klatt, 1980). Vowels consisting of two formants were synthesized based on the values reported by Peterson and Barney (1952). Fundamental frequency was fixed at 120 Hz, and the duration was fixed at 307 ms for all stimuli. Preliminary listening trials were required to determine the combination of $F1$ and $F2$ values that were the most appropriate for each of the vowels within the pair. These vowels were then played to five normal-hearing listeners, who recognized 100% of the test items.

TABLE I. Vowel formant-frequency values reported by Peterson and Barney (1952) for male talkers and those used in the present experiment. The formant levels are shown relative to the level of the formants that were equal for particular pairs.

Vowel	Peterson and Barney (1952) formant frequency values $F1$ (Hz)	$F2$ (Hz)	Formant frequency values used in test $F1$ (Hz)	$F2$ (Hz)	Formant level values used in test $L1$ (dB)	$L2$ (dB)
$F1$ different						
ɔ	570	840	570	855	5	0
ʉ	300	870	300	855	9	0
ɑ	730	1090	730	1055	− 5	0
ʊ	440	1020	440	1055	5	0
æ	660	1720	660	1780	15	0
ɛ	530	1840	530	1780	15	0
$F2$ different						
ɝ	490	1350	530	1350	0	− 12
ɛ	530	1840	530	1840	0	− 7
ɪ	390	1990	415	1990	0	− 10
ʊ	440	1020	415	1020	0	− 10
u	300	870	285	870	0	− 14
i	270	2290	285	2290	0	− 11

Table I shows the vowels and formant values used in the experiment, as well as those reported by Peterson and Barney (1952) for comparison. In the first set of vowels, each pair had the same second-formant frequency and level, and differed only in the first formant. In the second set of vowels, each pair had the same first-formant frequency and level, and differed only in the second formant. The use of identical levels for the constant formants within a vowel pair minimized intensity differences between those formants. The overall levels of the vowels ranged from 56–62 dB HL (ANSI, 1969), and different by 1–8 dB between vowels within a pair. Subjects reported that the vowels had the same loudness. Furthermore, the vowels were presented individually, and, without training, the subjects had little opportunity to determine small loudness differences across test runs.

D. Procedure

Stimuli were presented in soundfield via a Data Translation modification of a DEC-11/23 computer. The stimulus vowel pair, from which the subject had to choose, appeared orthographically on the touch-sensitive monitor together with an example of a familiar word: for example: "er" as in "heard" or "e" as in "head." A single stimulus was presented. Subjects recorded their responses by touching the appropriate word.

In a pretest practice session, subjects listened to the stimuli at least three times and until the experimenter was satisfied that the task was completely understood. They received no feedback during the practice session. In the test session, the six pairs of vowels were presented 30 times each. Each vowel was presented 15 times.

TABLE II. Results when only $F1$ differed between the two vowels. The values shown represent percent correct recognition when the stimulus and response alternatives were limited to the vowel pairs shown in the heading. Statistical significance greater than chance (50% correct) is shown (*) (74% correct) at the $p < 0.05$ level using the binomial model with each 30-item vowel-pair test (Thornton and Raffin, 1978).

Subjects	/ɔ/ vs /u/	Vowel pair /ɑ/ vs /ʊ/ Percent correct	/æ/ vs /ɛ/	$\bar{x}$
Cochlear				
IN1	54	87*	73	71
IN2	96*	97*	53	82
IN3	90*	90*	60	80
IN5	90*	87*	90*	89
M8	40	76*	66	61
	$\bar{x}$ = 74	87.4	68.4	76.6
Symbion				
IS1	100*	100*	83*	94
IS2	70*	87*	70*	76
IS3	83*	97*	93*	91
IS4	100*	63	60	74
CS1	90*	47	43	60
	$\bar{x}$ = 88.6	78.8	69.8	79

II. RESULTS

Table II shows the subjects' individual data, in percent correct, from each vowel pair when only $F1$ differed between the two vowels. For /ɔ/ vs /u/, three cochlear and five Symbion patients scored significantly above chance. For /ɑ/ vs /ʊ/, five Cochlear and three Symbion patients scored significantly above chance. For /æ/ vs /ɛ/, one cochlear and three Symbion patients scored above chance. Figure 1 shows the individual results averaged across vowels. The cochlear subjects' scores ranged from 61%–89% correct, with four of five subjects scoring significantly above chance. The Symbion subject scores ranged from 60%–94% correct with four of the five subjects scoring significantly above chance.

Table III shows individual data for each vowel pair when only $F2$ differed between the two vowels. For /ɝ/ vs /ɛ/, one cochlear and one Symbion patient scored significantly above chance. For /ɪ/ vs /ʊ/, three cochlear and three Symbion patients scored significantly above chance. For /i/ vs /u/, two cochlear and two Symbion patients scored significantly above chance. Figure 2 shows the individual results averaged across vowels. The Cochlear subject scores ranged from 54%–96% correct, with two of the five subjects scoring above chance. The Symbion subject scores ranged from 44%–94%, with three of the subjects scoring above chance.

Figure 3 shows average performance for both the Cochlear and Symbion subjects for each vowel pair when $F1$ differed. The vowel pairs are plotted as a function of the separation of $F1$. The $F1$ separation between the vowel pair /æ/ and /ɛ/ was 130 Hz, between /ɔ/ and /u/ was 270 Hz, and between /ɑ/ and /ʊ/ was 290 Hz. This ordering is based on absolute (not relative) frequency separation. The performance is higher for the two vowel pairs with the larger frequency differences.

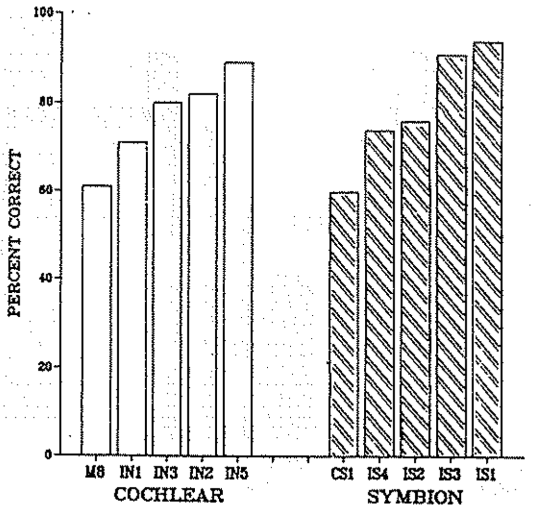

FIG. 1. Percent correct vowel recognition when $F1$ differed. Results are averaged over all vowel pairs. Chance performance is 50%, and statistical significance above chance is greater than 65% correct at the 95% confidence interval using the binomial model with a 90-item test.

Figure 4 shows similar results for each vowel pair when $F2$ differed. The $F2$ separation between the vowel pair /ɝ/ and /ɛ/ was 490 Hz, between /ɪ/ and /ʊ/ was 970 Hz, and between /i/ and /u/ was 1420 Hz. Again, performance is higher for the vowel pairs with the larger $F2$ differences.

III. DISCUSSION

These results suggest that some cochlear-implant subjects with the Symbion and cochlear devices use spectral information in speech recognition. All of the subjects scored above chance on at least one of the vowel-pair sets. However, this ability is far from perfect, as performance seldom reached 100% on this two-choice recognition task.

TABLE III. Results when only $F2$ differed between the two vowels. The values shown represent precent correct recognition when the stimulus and response alternatives were limited to the vowel pairs shown in the heading. Statistical significance greater than chance (50% correct) is shown (*) (74% correct) at the $p < 0.05$ level using the binomial model with each 30-item test (Thornton and Raffin, 1978).

Subjects	/ɝ/ vs /ɛ/	Vowel pair /ɪ/ vs /ʊ/ Percent correct	/i/ vs /u/	$\bar{x}$
Cochlear				
IN1	57	97*	97*	84
IN2	47	83*	50	60
IN3	93*	97*	97*	96
IN5	30	70	63	54
M8	43	66	70	60
	$\bar{x}$ = 54	82.6	75.4	70.8
Symbion				
IS1	30	50	53	44
IS2	60	43	63	55
IS3	36	97*	100*	77
IS4	83*	100*	100*	94
CS1	43	77*	66	62
	$\bar{x}$ = 50.4	73.4	76.4	66.4

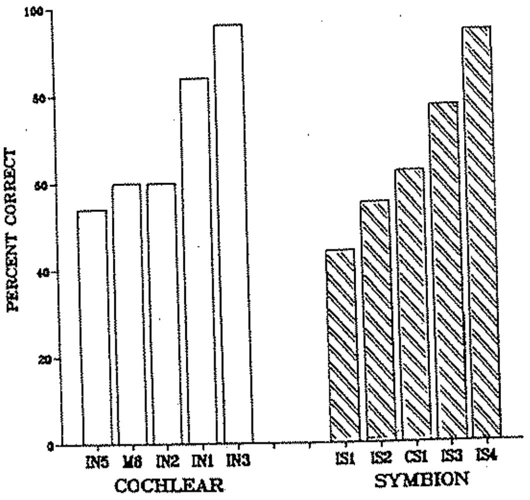

FIG. 2. Percent correct vowel recognition when $F2$ differed. Chance performance is 50%, and statistical significance above chance is greater than 65% correct at the 95% confidence interval using the binomial model with a 90-item test.

Other investigators have also reported that some implanted patients perceive spectral differences. White (1983) constructed two-formant synthetic vowels that differed only in $F1$ or only in $F2$. One subject with a single-channel prototype implant heard two vowels and then rated the difference between them on a 1–7 scale. The results suggested that this subject could discriminate the vowels that differed on $F1$ relatively well, but performed poorly on those vowels that differed on $F2$.

Dorman *et al.* (1988) studied the ability of one of the best Symbion users to identify synthesized vowels that differed only in $F2$ and the higher frequencies. The subject correctly identified 41% of the /bvt/ stimuli, which included 12 different vowels and diphthongs. Similarly, Merzenich (1985) reported that patients wearing the UCSF Stortz cochlear-implant device can distinguish between contrast vowel pairs when the second formants are coded on different channels, although specific details of the test procedure are not provided. Bilger (1977) reported results from a discrimination task where subjects were required to select the vowel that sounded different from three others. Although all of the eight subjects with the House single-channel device scored above chance on most of the vowel pairs, Bilger suggested that the subjects could have used intensity differences in their decisions.

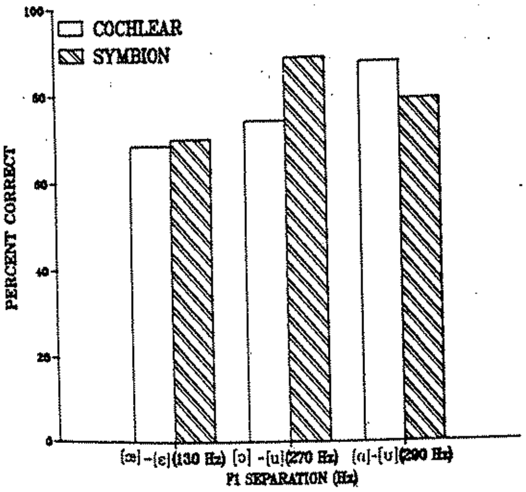

FIG. 3. Average results for Cochlear and Symbion subjects for vowel pairs that differed in $F1$.

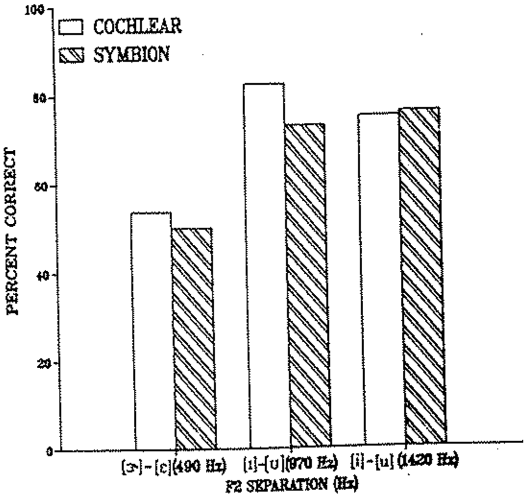

FIG. 4. Average results for Cochlear and Symbion subjects for vowel pairs that differed in $F2$.

While many subjects in the present study scored above chance when either $F1$ or $F2$ differed, it is of interest that those who performed well when $F1$ differed were not the same subjects as those who performed well when $F2$ differed. It is also true that the patients with the highest word recognition in sentence scores (IN2, CS1) were not the best performers on this steady-state vowel test. Other skills, particularly the perception of dynamic cues, will be important for the perception of sentences.

We discussed in the Introduction two ways in which spectral information might be coded: through the place of stimulation or the rate of neural discharge. For the Cochlear patients, only the place cue is available, since the pulse repetition rate of that device depends on the voicing frequency. Let us consider a vowel pair that differs in only one formant. The formant held constant will stimulate the same channel at the same current level for each vowel. The formant that differs will stimulate two different electrodes for the two vowels. When the formant level differs, the electrodes will also be stimulated at different levels. Higher levels can stimulate more neurons than lower level stimuli. The combined effect of different electrodes and levels could result in different nerve fibers being stimulated, depending upon nerve survival and current specificity. Thus the two vowels will be identified correctly if the two different formants stimulate different neurons *and* if this results in a different percept.

For the Cochlear patients, the vowel pairs that differed in $F1$ stimulated either an adjacent or adjacent-plus-one channel. These could be distinguished (see also Tong and Clark, 1985). For the /ɔ, u/ pair, the constant $F2$ of 855 Hz was less than the 1000-Hz $F2$ cutoff filter. Therefore, it is likely that the $F2$ electrode would have selected some arbitrary electrode, and recognition was based on the larger amplitude $F1$. Three cochlear patients scored 90% correct or better on this pair, so this dilemma does not necessarily have to result in degraded performance.

For the vowel pairs that differed in $F2$, the /ɝ, ɛ/ pair typically differed by three electrodes, and the /ɪ, ʊ/ by seven electrodes. The latter pair proved easier to recognize, with three out of five patients scoring above chance, compared to one out of five scoring above chance for the former pair.

For the /u, i/ pair, the $F2$ frequency values were 870 Hz for /u/ and 2290 Hz for /i/. This would nominally result in electrode differences of from 9 to 14 electrodes. However, the $F2$ for /u/ (870 Hz) was less than the $F2$ cutoff filter of 1000 Hz. Therefore, for /u/, the $F2$ electrode would have been uncertain. Two cochlear patients scored 97% correct with this pair, so this did not prevent the accurate demarcation of these two vowels.

For the Symbion patients, spectral information can be coded by place and rate of stimulation. When $F1$ varied, the /ɔ, u/ and /æ, ɛ/ pairs result in $F1$ values that both fall in channel 1. The different formant frequencies will result in different neural discharge rates. When the formants also differ in level, this could result in different neurons being activated. Higher level stimuli could activate more neurons, depending on the density and location of surviving neurons and current spread. Thus differences in formant frequency and level result in changes in the discharge rate and number of fibers responding at that rate. For the /ɑ, ʊ/ pair, $F1$ falls in channel 1 in /u/ and in channel 2 for /ɑ/. Thus differences in formant frequencies result in different place of stimulation and therefore different neurons. The rate cues would also be available.

It is interesting that the Symbion patients performed better for the /ɔ, u/ pair than for the /æ, ɛ/ pair (86% vs 70%). $F1$ was coded on channel 1 in both instances. This performance difference is presumably because of the closer frequency spacing in the latter /æ, ɛ/ pair, making rate cues more difficult to distinguish.

When $F2$ differed, one vowel had an $F2$ on channel 1 and the other vowel had an $F2$ on channel 3 in each of the vowel pairs. Therefore, both rate and place cues were available for all vowel-pair recognition tasks. Nonetheless, performance, in general, is clearly *not* superior for these Symbion patients on this $F2$-difference vowel pairs than on the $F1$-difference vowel pairs. This is probably related to the observation that rate discrimination is poorer at higher frequencies (Bilger, 1977). Although phase locking to electrical stimulation can be observed to frequencies as high as 4000 Hz (Javel *et al.*, 1987; Shepard *et al.*, 1983; Van der Honert and Stypulkowski, 1987), different frequencies above about 750–1500 Hz generally elicit the same pitch (Atlas *et al.*, 1983; Bilger, 1977; Eddington, 1980; Townshend *et al.*, 1987).

Since monopolar stimulation results in a fairly broad pattern of current stimulation, it is noteworthy that the Symbion device may be providing place-specific coding. However, the present investigation does not specifically address the degree to which the Symbion patients are utilizing place or rate information (or both).

One might expect that the frequency differences between the formants in the vowel pairs has a major effect on performance. When $F1$ differed, clearly the /ɔ, u/ pair (270-Hz difference) and the /ɑ, ʊ/ pair (290-Hz difference) resulted in higher performance than with the /æ, ɛ/ pair (130-Hz difference). When $F2$ differed, poorer performance was again observed with the smallest frequency separation /ɝ, ɛ/ (490 Hz). However, subject performance on the /ɪ, ʊ/ and /i, u/ pairs were similar in spite of a 970-Hz difference in the former and a 1420-Hz difference in the latter. The lack of a clear relationship between frequency separation of vowel formant frequencies and performance is probably related to the fact that the absolute frequency separation in between vowels actually occurs in different frequency regions. In addition, the relationship between the formant frequencies and the particular electrodes being stimulated is probably critical. This suggests that a careful rearrangement of filter bandwidths might improve performance in some patients, particularly those with poor perceptual skills.

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ANSI (1969). "Specifications for audiometers" (American National Standards Institute, New York).

Atlas, L. E., Herndon, M. K., Simmons, F. B., Dent, L. J., and White, R. L. (1983). "Results of stimulus and speech-coding schemes applied to multichannel electrodes," in *Cochlear Prostheses: An International Symposium*, edited by C. W. Parkins and S. W. Anderson (New York Academy of Sciences, New York), pp. 377–386.

Banfai, P., Hortmann, G., Karczag, A., Kubik, S., and Wustrow, F. (1984). "Results with eight-channel cochlear implants," Adv. Audiol. **2**, 1–18.

Bilger, R. C. (1977). "Psychoacoustic evaluation of present prostheses," Ann. Otol. Rhinol. Laryngol. **86** (Suppl. 38), 92–140.

Blamey, P. J., Dowell, R. C., Brown, A. M., Clark, G. M., and Seligman, P. M. (1987a). "Vowel and consonant recognition of cochlear implant patients using formant-estimating speech processors," J. Acoust. Soc. Am. **82**, 48–57.

Blamey, P. J., Dowell, R. C., Clark, G. M., and Seligman, P. M. (1987b). "Acoustic parameters measured by a formant-estimating speech processor for a multiple-channel cochlear implant," J. Acoust. Soc. Am. **82**, 38–47.

Cohen, N. L., Waltzman, S. B., and Shapiro, W. H. (1985). "Clinical trials with a 22-channel cochlear prosthesis," Laryngoscope **95**, 1448–1454.

Dorman, M. F., Dankowski, K., McCandless, G., and Smith, L. (1989a). "Identification of synthetic vowels by patients using the Symbion multichannel cochlear implant," Ear Hear. **10**, 40–43.

Dorman, M. F., Hannley, M. T., Dankowski, K., Smith, L., and McCandless, G. (1989b). "Word recognition by 50 patients fitted with the Symbion multichannel cochlear implant," Ear Hear. **10**, 44–49.

Dorman, M. F., Hannley, M. T., McCandless, G. A., and Smith, L. M. (1988). "Auditory/phonetic categorization with the Symbion multichannel cochlear implant," J. Acoust. Soc. Am. **84**, 501–510.

Eddington, D. K. (1980). "Speech discrimination in deaf subjects with cochlear implants," J. Acoust. Soc. Am. **68**, 885–891.

Gantz, B. J., Tyler, R. S., Knutson, J. F., Woodworth, G., Abbas, P. J., McCabe, B. F., Hinrichs, J., Tye-Murray, N., Lansing, C., Kuk, F., and Brown, C. (**1988**). "Evaluation of five different cochlear implant designs: Audiologic assessment and predictors of performance," Laryngoscope **98**, 1100–1106.

Hochmair, E. S., and Hochmair-Desoyer, I. J. (**1985**). "Aspects of sound signal processing using the Vienna intra- and extracochlear implants," in *Cochlear Implants*, edited by R. A. Schindler and M. M. Merzenich (Raven, New York), pp. 101–110.

Hopkinson, N. T., McFarland, W. H., Owens, E., Reed, C., Shallop, J., Tillman, T., Tyler, R. S., and Williams, P. S. (**1986**). "Report of the Ad Hoc Committee on cochlear implants," ASHA **28** (4), 29–52.

Javel, E., Tong, Y. C., Shepherd, R. K., and Clark, G. M. (**1987**). "Responses of cat auditory nerve fibers to biphasic electrical current pulses," Ann. Otol. Rhinol. Laryngol. **96** (Suppl. 128), 26–30.

Klatt, D. H. (**1980**). "Software for a cascade/parallel formant synthesizer," J. Acoust. Soc. Am. **67**, 971–995.

Merzenich, M. M. (**1985**). "UCSF cochlear implant device," in *Cochlear Implants*, edited by R. A. Schindler and M. M. Merzenich (Raven, New York), pp. 121–129.

Peterson, G. E., and Barney, H. L. (**1952**). "Control methods used in a study of the vowels," J. Acoust. Soc. Am. **24**, 175–184.

Rosen, S., Walliker, J., Brimacombe, J. A., and Edgerton, B. J. (**1989**). "Prosodic and segmental aspects of speech perception with the House/3M single-channel implant," J. Speech Hear. Res. **32**, 93–111.

Shepard, R. K., Clark, G. M., and Black, R. C. (**1983**). "Chronic electrical stimulation of the auditory nerve in cats," Acta Otolaryngol. (Suppl.) **399**, 19–31.

Thornton, A. R., and Raffin, M. J. M. (**1978**). "Speech-discrimination scores modeled as a binomial variable," J. Speech Hear. Res. **21**, 507–518.

Tong, Y. C., and Clark, G. M. (**1985**). "Absolute identification of electric pulse rates and electrode positions by cochlear implant patients," J. Acoust. Soc. Am. **77**, 1881–1888.

Townshend, B., Cotter, N., Van Compernolle, D., and White, R. L. (**1987**). "Pitch perception by cochlear implant subjects," J. Acoust. Soc. Am. **82**, 106–115.

Tyler, R. S. (**1988a**). "Open-set word recognition with the 3M/Vienna single-channel cochlear implant," Arch. Otolaryngol.—Head Neck Surg. **114**, 1123–1126.

Tyler, R. S. (**1988b**). "Open-set word recognition with the Duren/Cologne extracochlear implant," Laryngoscope **98** (9), 999–1002.

Tyler, R. S., Preece, J. P., and Tye-Murray, N. (**1986**). "Audiovisual tests of lipreading" (laser videodisc).

Tyler, R. S., Tye-Murray, N., Moore, B. C. J., and McCabe, B. F. (**1989**). Synthetic two-formant vowel perception by some of the better cochlear-implant patients. Audiology (in press).

Van der Honert, C., and Stypulkowski, P. H. (**1987**). "Temporal response patterns of single auditory nerve fibers elicited by periodic electrical stimuli," Hear. Res. **29**, 207–222.

Van Tasell, D. J., Soli, S. D., Kirby, V. M., and Widin, G. P. (**1987**). "Speech waveform envelope cues for consonant recognition," J. Acoust. Soc. Am. **82**, 1152–1161.

White, M. W. (**1983**). "Formant frequency discrimination and recognition in subjects implanted with intracochlear stimulating electrodes," in *Cochlear Prostheses: An International Symposium*, edited by C. W. Parkins and S. W. Anderson (New York Academy of Sciences, New York), pp. 348–359.