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First Quarterly Progress Report

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"Speech Processors for Auditory Prostheses"

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I. Introduction

The purpose of this project is to design and evaluate speech processors for implantable auditory prostheses. Ideally, the processors will extract (or preserve) from speech those parameters that are essential for intelligibility and then appropriately encode these parameters for electrical stimulation of the auditory nerve or central auditory structures. Work in the present quarter included the following:

1. Studies with one patient implanted with the Symbion device (MP) and one implanted with the Nucleus device (HP). The studies with the Symbion patient were conducted in collaboration with Drs. Donald Eddington and William Rabinowitz of the Massachusetts Eye and Ear Infirmary and Massachusetts Institute of Technology. The studies with the Nucleus patient were conducted in collaboration with Dr. Margaret Skinner of the Washington University School of Medicine and with Dr. Bryan Pfingst of the Kresge Hearing Research Institute at the University of Michigan.
2. Further refinement of computer interface systems (based on the TMS320C25 processor) for studies with patients implanted with these devices.
3. Initiation of frequency discrimination studies in collaboration with Dr. Pfingst, to evaluate possible effects of electrode coupling configuration (e.g., monopolar *versus* bipolar), stimulus waveshape (e.g., short duration pulses *versus* long duration pulses), and electrode location within the cochlea. Pilot studies were conducted with patients HP and MP.
4. Development of psychophysical test software for the above frequency discrimination studies. (This primarily consisted of implementing the method of constant stimuli for these studies).
5. Further development of matrix aggregation and analysis software.
6. Completion of work to convert the laboratory from the Eclipse computing environment to the 80386 computing environment (see Quarterly Progress Report 11, NIH project N01-NS-5-2396).
7. Continued analysis of data from studies conducted in the previous quarter with patients RB and SW.
8. Further development of finite-element models of the electric fields produced by various types of intracochlear electrodes.
9. Preparation for, and participation in, the Engineering Foundation Conference on "Implantable Auditory Prostheses," held in Potosi, MO, July 30 through August 4, 1989.
10. Continued preparation of manuscripts for publication.

In this report we will present results from recent studies with two patients implanted with the Symbion device (patients RB and MP, who are identified as subjects 7 and 8 in the following section). To place these results in perspective with results from previous studies with patients implanted with the UCSF/Storz device, we also will review briefly those earlier results. Results from the other studies indicated in points 1, 3 and 8 above will be presented in future reports.

II. Comparison of Analog and Pulsatile Coding Strategies for Multichannel Cochlear Prostheses

In studies conducted in collaboration with investigators at the University of California at San Francisco (UCSF), our team compared a variety of speech processing strategies in tests with patients implanted with the UCSF/Storz electrode array [Wilson et al., 1988a,b,c; Wilson et al., 1989]. Some of the largest differences in performance among processing strategies were found in comparisons between the compressed analog (CA) processor of the present UCSF/Storz prosthesis and a type of "interleaved pulses" (IP) processor which delivers pulses in sequence to the different channels in the implanted electrode array.

In more recent studies, conducted in collaboration with D.K. Eddington and W.M. Rabinowitz of the Massachusetts Eye and Ear Infirmary and the Massachusetts Institute of Technology, we have extended the comparisons of CA and IP processors to patients implanted with the Symbion electrode array. These later studies are of particular interest inasmuch as the UCSF/Storz and Symbion electrode arrays have fundamentally different designs.

The purpose of the present report is to describe the results obtained with both sets of patients. In particular, results from tests of consonant and vowel identification will be presented, as will results from the open-set tests of the Minimal Auditory Capabilities (MAC) battery [Owens et al., 1985].

Processing Strategies

Four channels of CA stimulation are used in both the UCSF/Storz and Symbion cochlear prostheses. These stimuli are delivered either to alternate pairs of "radial bipolar" electrodes in the UCSF/Storz device or to the apical four (of six) monopolar electrodes in the Symbion device. The locations of active electrode sites are spaced 4.0 mm apart for both devices, and the depth of electrode array insertion into the scala tympani is similar for the two devices (between 20 and 25 mm for a full insertion). Results from modeling [e.g., Finley et al., 1989] and electrophysiological [e.g., van den Honert and Stypulkowski, 1987] studies indicate that the spatial selectivity of neural excitation may be much greater for radial bipolar electrodes than for monopolar electrodes, at least for implanted ears in which nerve survival is good.

The basic functions of the CA processor are first to compress the wide dynamic range of input speech signals into the narrow dynamic range available for electrical stimulation and then to filter the compressed signal into individual frequency bands for presentation to each electrode. Typical waveforms of the CA processor are shown in Fig. 1. The top trace in each panel is the input signal, which in this case is the word "bought." The other waveforms in each panel are the filtered output signals for four channels of intracochlear stimulation. The bottom left panel shows an expanded display of waveforms during the initial part of the vowel in "bought," and the bottom right panel shows an expanded display of waveforms during the final /t/. The lower panels in Fig. 1 thus exemplify differences in waveforms for voiced and unvoiced intervals of speech.

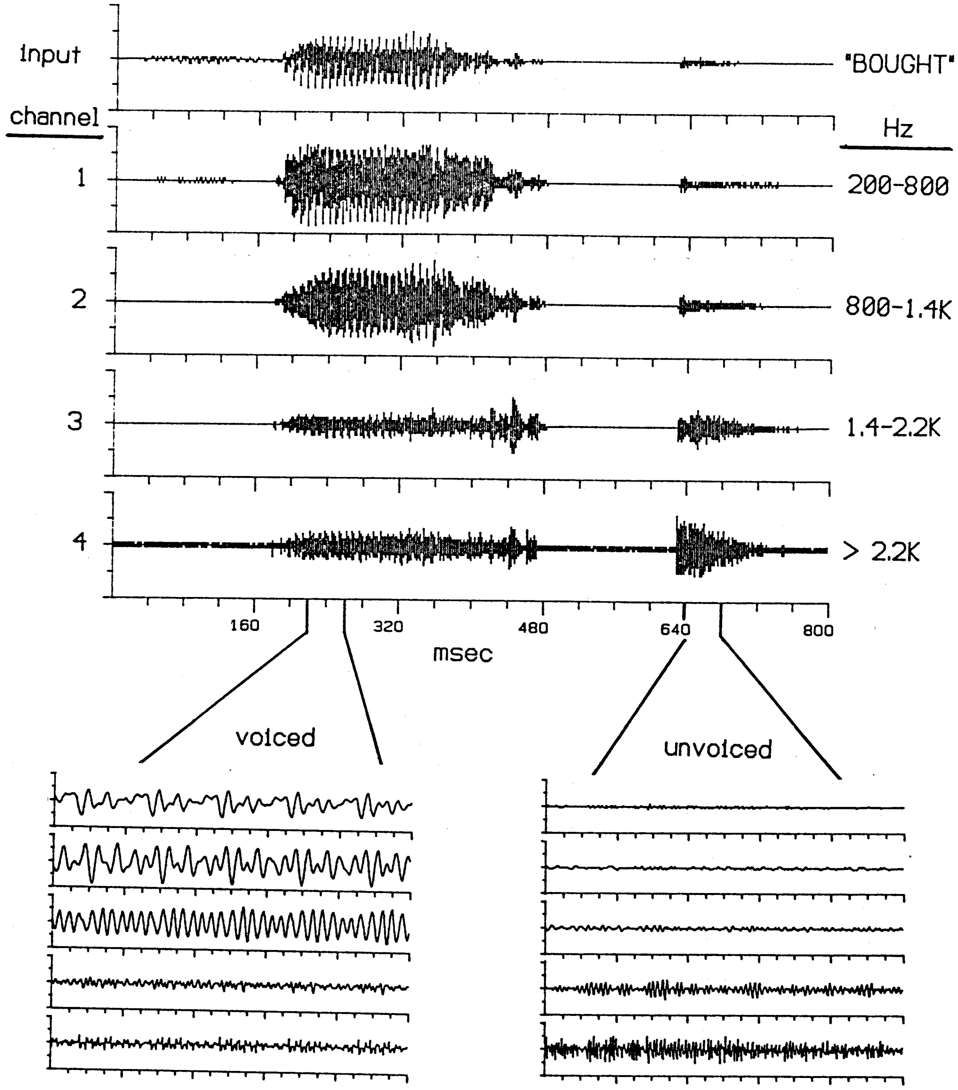

Fig. 1. Waveforms of a compressed analog (CA) processor.

In the voiced interval the relatively large outputs of channels 1 and 2 reflect the low-frequency formant content of the vowel, and in the unvoiced interval the relatively large outputs of channels 3 and 4 reflect the high-frequency noise content of the /t/. In addition, the clear periodicity in the waveforms of channels 1 and 2 reflects the fundamental and first formant frequencies of the vowel during the voiced interval, and the lack of periodicity in the output of any channel reflects the noiselike quality of the /t/ during the unvoiced interval. As has been described elsewhere, this representation of speech features can support high levels of open-set recognition for many (but not all) of the patients implanted either with the UCSF/Storz [Schindler and Kessler, 1987; Schindler et al., 1986, 1987] or the Symbion [Eddington, 1983; Gantz et al., 1988] prosthesis.

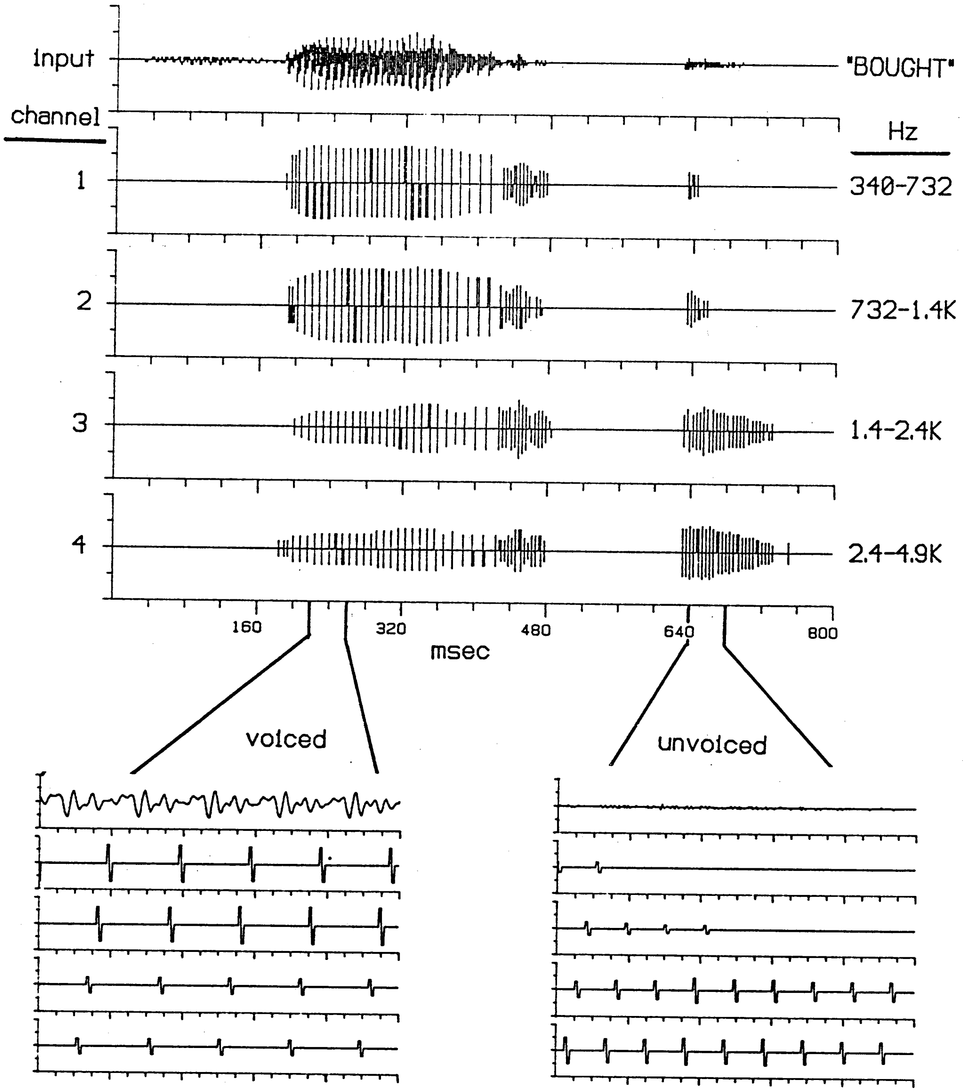

Fig. 2. Waveforms of an interleaved pulses (IP) processor.

A concern associated with the use of multichannel CA processors is that of channel interactions [White et al., 1984]. Simultaneous stimulation of two or more channels with continuous waveforms results in summation of the electrical fields from the individual electrodes. This summation can exacerbate interactions among channels, especially for patients who require high stimulation levels. Summation of stimuli from multiple channels also depends on the phase relationships among the waveforms. Because these relationships are not controlled in a multichannel CA processor, the representation of the speech spectrum may be further distorted by continuously changing patterns of channel interaction. A reduction of channel interactions might increase the salience of channel-related cues for implant patients.

The problem of channel interactions is addressed in the IP processor of Fig. 2 through the use of nonsimultaneous stimuli. There is no temporal overlap between stimulus pulses, so that direct summation of electrical fields produced by different electrode channels is avoided. The energy in each frequency band of the input signal is coded as the amplitude of the pulses delivered to the corresponding stimulus channel. Distinctions between voiced and unvoiced segments of speech are represented by the timing of cycles of stimulation across the electrode array. In this particular IP processor stimulation cycles are timed to occur in synchrony with the detected fundamental frequency for voiced speech sounds and at the maximum rate (with one stimulation cycle immediately following its predecessor) for unvoiced speech sounds. The timing of stimulation cycles for voiced and unvoiced intervals can be seen in the lower panels of Fig. 2.

Subjects

Six patients implanted with the UCSF/Storz electrode array [Loeb et al., 1983; Merzenich, 1985] and two patients implanted with the Symbion electrode array [Eddington, 1983] participated as subjects. Tests with the CA processor were conducted with each patient's clinical device, and tests with the IP processor were conducted either with computer simulations [Wilson and Finley, 1985] or with a real-time, microprocessor-based instrument [Finley et al., 1987].

Each subject was studied for a one-week period in which (a) basic psychophysical measures were obtained on thresholds and dynamic ranges for pulsatile stimuli, (b) a variety of IP processors (with different choices of processor parameters) was evaluated with tests of vowel and consonant identification, and (c) the best of these IP processors was further evaluated using a broad spectrum of speech tests.

It is important to note that certain attributes of these subjects favored the CA processor in comparisons of the CA and IP strategies. First, all eight subjects entered the study with substantial experience using the CA processor. The average experience with that processor exceeded 1 year of daily use. In contrast, experience with the IP processor was limited to that obtained in a 6-day period of testing a variety of processors with each subject. As discussed in detail elsewhere [Dowell et al., 1987; Tyler et al., 1986; Wilson et al., 1988c], such a disparity in experience might strongly favor the CA processor.

An additional factor weighing against the IP processor for the UCSF/Storz subjects was the use of a four-channel transcutaneous transmission system (TTS) for sending stimulus information to the implanted electrodes. The principal limitations of that system for IP processors were (a) inadequate levels of voltage compliance for stimulation with short-duration pulses, (b) the small number of channels, (c) limited frequency response of each TTS channel (approximately 300 to 7000 Hz), and (d) lack of current control in the stimulus waveforms. Half of the UCSF/Storz subjects were further limited to fewer than four channels due to a mode of TTS failure [Schindler et al., 1986]. Because results from preliminary studies with percutaneous cable patients indicate that optimized fittings of IP processors require at least six channels of stimulation and short-duration pulses [Wilson et al., 1988a,b], it seems likely that the present fittings of IP processors were less

Table 1. Parameters of IP processors for the UCSF/Storz subjects.*

Subject	Channels	Pulse Widths/Phase (ms)	Pulse Sep. (ms)	Cycle Time (ms)
1	3	0.5	0.5	4.5
2	4	0.5	0.5	6.0
3	3	1.0	0.1	6.3
4	2	0.5	0.1	2.2
5	4	1.0 1.0 0.5 0.5	0.1	6.4
6	4	0.3 0.7 0.3 0.3	0.5	5.2

*All processors used symmetric biphasic pulses with the positive phase leading and with the channels stimulated in base-to-apex order. Stimulation cycles were presented at the fundamental frequency during voiced speech sounds and at the maximum rate (period equal to cycle time) during unvoiced speech sounds.

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than ideal for the UCSF/Storz subjects.

The parameters selected for the IP processors used by each of the six UCSF/Storz subjects (subjects 1-6) are presented in Table 1. The best fulfillments of the fitting criteria for IP processors [Wilson et al., 1988b] were obtained for subjects 2 and 6. Each had the use of all four stimulation channels, and the average pulse width across channels was 0.5 ms/phase or less for these two subjects.

In contrast, relatively poor sets of parameters had to be used for the remaining subjects. Subjects 1 and 3 had only three usable channels for pulsatile stimulation (with phase durations of 1.0 ms or less) and subject 4 only two. In addition, long pulse durations (1.0 ms/phase) had to be used for subjects 3 and 5.

With the exception of subject 4, each of the UCSF/Storz subjects had the same number of usable channels for the CA and IP processors. Subject 4 had

Table 2. Parameters of IP processors for the Symbion subjects.*

			Pulses				Update Order	
Subj	Proc	Chans	dur/ph	sep	+/-	v/uv	v	uv
7	Rb1a	6	0.1	0.3	-	Y	6,5,4,3,2,1	6,5,4,3,2,1
	Rb1b	6	0.1	0.3	+	Y	6,5,4,3,2,1	6,5,4,3,2,1
8	4I	4	0.1	0.4	+	Y	4,3,2,1	random
	1I	6	0.1	0.4	+	Y	6,5,4,3,2,1	random
	1A	6	0.1	0.4	+	Y	6,5,4,3,2,1	6,5,4,3,2,1
	1L	6	0.1	0.4	+	Y	6,3,5,2,4,1	6,3,5,2,4,1
	1B	6	0.1	0.4	+	N	6,5,4,3,2,1	

*All processors used symmetric biphasic pulses with the indicated phase leading at the "active," intracochlear electrode. Except for processor 1B (the last processor in the list for subject 8), stimulation cycles were presented at the fundamental frequency during voiced speech sounds and at either the maximum rate (period equal to cycle time, processors 4I, 1I, 1A and 1L) or randomly-varied intervals (period between 3.0 and 7.0 ms, processors Rb1a and Rb1b) during unvoiced speech sounds. Stimulation cycles were presented at the maximum rate (278 Hz) during both voiced and unvoiced speech sounds with processor 1B.

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the use of his apical-most channel for CA stimulation but not for IP stimulation. Low-frequency analog stimuli presented to that channel produced auditory percepts for subject 4 while 1.0 ms/phase pulses did not. The remaining two available channels for subject 4 were used in both the CA and IP processors.

transcutaneous telemetry system

Because the Symbion prosthesis has a percutaneous connector for direct electrical access to the implanted electrodes, implementations of IP processors were not constrained by the limitations of a TTS for the Symbion subjects. Therefore, a greater range of processor variations was used in the studies with those subjects. Processors evaluated in tests with the Symbion subjects (subjects 7 and 8) are described in Table 2. The two IP processors evaluated in the tests with subject 7 were identical in all respects except for the polarity of the leading phase of pulses delivered to the active electrodes within the scala tympani. In processor Rb1a the leading phase was negative, and in processor Rb1b the leading phase was positive. This manipulation was made to test the idea that an initially cathodic phase might produce a more localized field of neural excitation around the active electrode than the field produced with an initially anodic phase [see, e.g., Ranck, 1975]. A more localized excitation field might in turn lead to an improved representation of frequencies in terms of the site of intracochlear stimulation.

Both IP processors used in the studies with subject 7 had six channels of stimulation and a relatively short stimulation cycle time of 3.0 ms. These favorable values were made possible by the direct percutaneous access to the implanted electrodes.

The choice of processors for the studies with subject 8 was in part guided by the observation with subject 7 that the processor with a positive leading phase of pulses delivered to the active electrodes (Rb1b) produced higher scores on the consonant and vowel identification tests than the processor with negative-leading pulses (Rb1a). Although this result was somewhat surprising, we decided to use positive-leading pulses for all processors evaluated with subject 8. In addition, all processors for subject 8 used 0.1 ms/phase pulses with 0.4 ms separating sequential pulses. These pulse parameters produced stimulation cycle times of 2.4 ms for the four-channel IP processor (4I) and 3.6 ms for the six-channel IP processors (1I, 1A, 1L and 1B).

Manipulations in processor design for the studies with subject 8 included (a) the number of stimulation channels, (b) the order of channel updates within each stimulation cycle, and (c) the way in which pulses were delivered during voiced and unvoiced speech sounds. The number of stimulation channels was either 4 or 6. Processors 4I and 1I were identical in all respects except for the number of stimulation channels. Thus, comparison of results obtained with those two processors was useful for confirmation of previous findings of increased performance when the number of channels for an IP processor is increased from 4 to 6 [Wilson et al., 1988a,b]. In addition, processor 4I (the four-channel IP processor) provided a direct comparison with the four-channel CA processor of the Symbion prosthesis.

The order of channel updates was either from base-to-apex (4,3,2,1 and 6,5,4,3,2,1), as in the previous studies with subjects 1-7, or one designed to produce the maximum spatial separation between sequentially-stimulated electrodes (6,3,5,2,4,1). The first order mimics the base-to-apex progression of neural excitation imposed by the traveling wave of basilar membrane vibrations in normal hearing, while the second order might be expected to provide reductions in channel interactions beyond those already provided with the use of nonsimultaneous stimuli. Processors 1A and 1L were identical in all respects except for the order of channel updates.

The final set of manipulations involved the way in which pulses were delivered during voiced and unvoiced speech sounds. As indicated before, IP processors generally have presented stimulation cycles at the fundamental frequency during voiced speech sounds and at either the maximum rate or randomly-varied intervals during unvoiced speech sounds. In addition, the channel update order generally has been the same for stimulation cycles during both types of sounds.

Two variations of this general design were evaluated in the studies with subject 8. In the first variation the order of channel updates was randomized during unvoiced speech sounds. This variation was suggested by recent findings of the Melbourne group [Tong et al., 1989], which indicated that a randomized ordering of channel updates can produce a "scratchy" or "fuzzy" noiselike percept compared with "smoother" percepts produced with fixed orders of channel updates. Inasmuch as unvoiced speech sounds are noiselike in character, a randomized update order during those sounds might improve the apparent fidelity of the representation and might also increase the salience of voiced/unvoiced distinctions. Processors 4I and 1I used randomized orders of channel updates during unvoiced speech sounds, and processors 1I and 1A were identical in all respects except that processor 1A used a fixed order of channel updates during unvoiced speech sounds.

The second variation of voiced/unvoiced coding was to eliminate that coding by presenting stimulation cycles at the maximum rate during both voiced and unvoiced speech sounds. This variation increased the "temporal density" of stimulation during voiced speech sounds, and also eliminated the need for the processor to make the voiced/unvoiced decision. Processors 1A and 1B were identical in all respects except that stimulation cycles were presented at the maximum rate (278 Hz) during both voiced and unvoiced speech sounds with processor 1B.

Tests

Most of the results presented in this report are from tests of consonant and vowel identification. The speech tokens included in these tests are listed in Table 3. The first three tests (Iowa videotape test and two RTI tests, see below) were used in the studies with the UCSF/Storz subjects, and the last two (Iowa videodisc tests) in the studies with the Symbion subjects.

As indicated, two consonant tests were used in the studies with the UCSF/Storz subjects. The first was the one developed at the University of Iowa for measurement of audiovisual consonant perception [Tyler et al., 1983]. A video tape of an adult male speaker provided the visual component of each presentation. The audio track of the tape provided an input to the UCSF/Storz processor or the real-time IP processor via direct connection. Each consonant was presented five times in a randomized list of stimulus presentations. After each presentation, the subject responded by pointing to one choice in a table of the 14 response options. No feedback on correct or incorrect responses was provided. Finally, the order of testing for the different conditions was designed to confer any benefits of learning on the CA processor. The order was first to test the IP processor plus vision, then vision alone, and then the CA processor plus vision.

A matrix of stimuli and responses was compiled for each subject and condition. The matrices then were summed across subjects for each of the conditions. These summed matrices provided the inputs to the analyses

Table 3. Tokens used in the tests of consonant and vowel identification.

Test	Context	Phonemes
Iowa, videotape	/aCa/	b, d, f, g, dʒ, k, m, n, p, s, ʃ, t, v, z
RTI	/aCa/	d, k, l, n, s, t, ð, z
RTI	/bVt/	i, ɔ, o, u, I
Iowa, videodisc	/aCa/	b, d, f, g, dʒ, k, l, m, n, p, s, ʃ, t, ð, v, z
Iowa, videodisc	/hVd/	i, ɔ, ɛ, u, I, U, ʌ, æ

described in the Results sections of this report.

The second consonant test used in the studies with the UCSF/Storz subjects was one suggested by Earl Schubert [1985]. The consonants are those with a nonlabial place of articulation and with high frequencies of occurrence in spoken English. Because consonants with nonlabial places of articulation are difficult or impossible to distinguish with speechreading alone, Schubert reasoned that a pragmatic approach to processor design and evaluation would be to concentrate on these important (but largely invisible) consonants.

The vowel test used for the UCSF/Storz subjects was designed to measure the ability to discriminate relatively large differences in the first and second formant frequencies among the selected vowels.

Single exemplars of the tokens in the last two tests (referred to as the RTI tests) were recorded and digitized from representative utterances of an adult male speaker. The digitized tokens were used as inputs to the UCSF/Storz processor (after appropriate digital-to-analog conversion) or the computer simulation of the IP processor. A single block of trials included three presentations of each of the consonants or five presentations each of the vowels in random order. Multiple repetitions of a token were available at regular intervals during each presentation. At the beginning of each presentation a display of response options was shown on a computer terminal used by the subject. The subject responded by touching a key on the terminal. Usually a response was entered after the first or second repetition. At the end of a block, the subject was given the overall percent correct score and an indication of the principal confusions made during the test. With few exceptions, no feedback was given during a block. In the exceptional cases (12 out of 137 blocks), feedback was provided across conditions so that no processor would receive an advantage over another.

Table 4. Number of presentations of each token in the RTI tests for the indicated subjects.

		Condition*				
Test	Subject	V	CA+V	IP+V	CA	IP
Consonant	1	3	9	15	9	18
	2	6	6	9	3	9
	3	9	9	6	9	6
	4	6	6	9	6	12
	5	3	6	6	9	6
	6	6	3	6	3	6
Vowel	1	10	15	10	15	10
	2	10	10	30	15	15
	3	15	10	5	10	5
	4	10	10	10	10	10
	5	5	10	5	10	5
	6	10	10	10	10	10

*Abbreviations are V for Vision, CA+V for compressed analog plus vision, IP+V for interleaved pulses plus vision, CA for compressed analog only, and IP for interleaved pulses only.

The conditions for both RTI tests included vision only, CA processor plus vision, IP processor plus vision, CA processor only, and IP processor only. For the conditions with a visual component, speechreading information was provided by miming the tokens in synchrony with the stimulus repetitions. The same person (DTL) mimed the tokens for all subjects.

Blocks of trials were repeated as time permitted during the six days of testing with each subject. Because many other tests were being conducted during this same period [Wilson et al., 1988b,c], the total number of trials for the RTI tests was not uniform across subjects and conditions. The actual totals are presented in Table 4. For the great majority of subjects and conditions, the number of trials with each token for the consonant test was 6 or more, and the number for the vowel test was 10 or more.

As with the Iowa videotape test, matrices of stimuli and responses were compiled for all subjects and conditions. Each RTI matrix was normalized to show the fraction of responses in each cell, and the normalized matrices were then summed across subjects for each of the conditions. The estimates of matrix responses calculated in this way reflect balanced contributions from all subjects for each condition while still using all of the available data.

As mentioned before, a different set of consonant and vowel tests was used in the studies with the Symbion subjects. The tests with the Symbion subjects were conducted with the newly available laser videodisc materials from the University of Iowa [Tyler et al., 1987]. These materials provided (a) multiple exemplars of consonant and vowel tokens spoken by both male and female speakers, (b) a larger, more representative set of consonants and vowels than were available in our previously-recorded RTI tests or in the older Iowa videotape test, (c) much better control of visual cues than in the RTI tests, (d) computer control of videodisc playback, which greatly facilitated randomization of tokens and greatly reduced the time required to complete a block of trials with a given number of tokens. Although we were reluctant to use different sets of tests for the two groups of subjects, we felt that the advantages of the new tests (for the Symbion subjects) outweighed the obvious disadvantage of comparing results from different tests.

A single block of trials for the Iowa videodisc tests included five presentations of each of the 16 consonants or three presentations of each of the 8 vowels. After each presentation, the subject responded by identifying one of the tokens in a video display of response options. No feedback on correct or incorrect responses was provided. Blocks of trials were repeated as time permitted during the six days of testing with each subject. The total number of trials for subjects 7 and 8 are presented in Table 5. For all subjects and conditions, the number of trials for the consonant test was 10 or more, and the number for the vowel test was 12 or more. Aggregate matrices of stimuli and responses were compiled and summed for a variety of conditions (see Results) using the procedure outlined above for the RTI matrices.

In addition to the tests of consonant and vowel identification, the CA and IP processors were further evaluated for both the UCSF/Storz and Symbion subjects with an extensive series of speech perception tests. These additional tests included all subtests of the MAC battery [Owens et al., 1985] and connected discourse tracking with and without the prosthesis [De Filippo and Scott, 1978; Owens and Raggio, 1987]. The results from the subtests of the MAC battery designed to measure open-set recognition will be discussed in this report.

Consonant and Vowel Identification, UCSF/Storz Subjects

To evaluate the patterns of confusions (and correct responses) from the tests of consonant and vowel identification, the combined matrix for the responses of all subjects for each condition was used as an input to the information transmission (IT) analysis of Miller and Nicely [1955]. In this analysis the "relative transinformation" is calculated for selected articulatory or acoustic features of the phonemes in the identification tests. The relative transinformation score for each feature, expressed here as percent information transfer, indicates how well that feature was transmitted to the subjects. The consonant features selected for the present study were voicing (voice), nasality (nasal), place of articulation (place), duration (durat), frication (fric), envelope cues (envel), and visual cues (viseme). The vowel features were first formant frequency (F1), second formant frequency (F2), duration (durat), and visual cues (viseme).

Table 5. Number of presentations of each token in the Iowa laserdisc tests for the indicated subjects.

			Condition*		
Test	Subject	Processor	A	AV	V
Consonant	7	none			10
		CA	25	15	
		Rb1a	20	35	
		Rb1b	20	20	
	8	none			10
		CA	30	20	
		4I	20	10	
		1I	20	10	
		1A	20	15	
		1L	20	15	
		1B	20	10	
Vowel	7	none			12
		CA	24	12	
		Rb1a	24	24	
		Rb1b	12	12	
	8	none			18
		CA	15	12	
		4I	18	15	
		1I	15	15	
		1A	DNT	DNT	
		1L	DNT	DNT	
		1B	12	12	

*Abbreviations are A for Audition only, AV for Audition plus Vision, and V for Vision only.

The results from IT analysis of the Iowa videotape matrices (/p, b, m, f, v, ʃ, dʒ, s, z, t, d, n, g, k/, subjects 1-6) are presented in Fig. 3. The open bars show IT scores for the vision-only condition, the bars with diagonal lines show the scores for the CA-processor-plus-vision condition, and the solid bars show the scores for the IP-processor-plus-vision condition. Note that the viseme and place features are transmitted equally well for all three conditions. The high score for place in the vision-only condition is indicative of the high redundancy between assignments for the place and viseme features. That is, a front (bilabial and labiodental) place of articulation usually can be distinguished from other places of articulation through

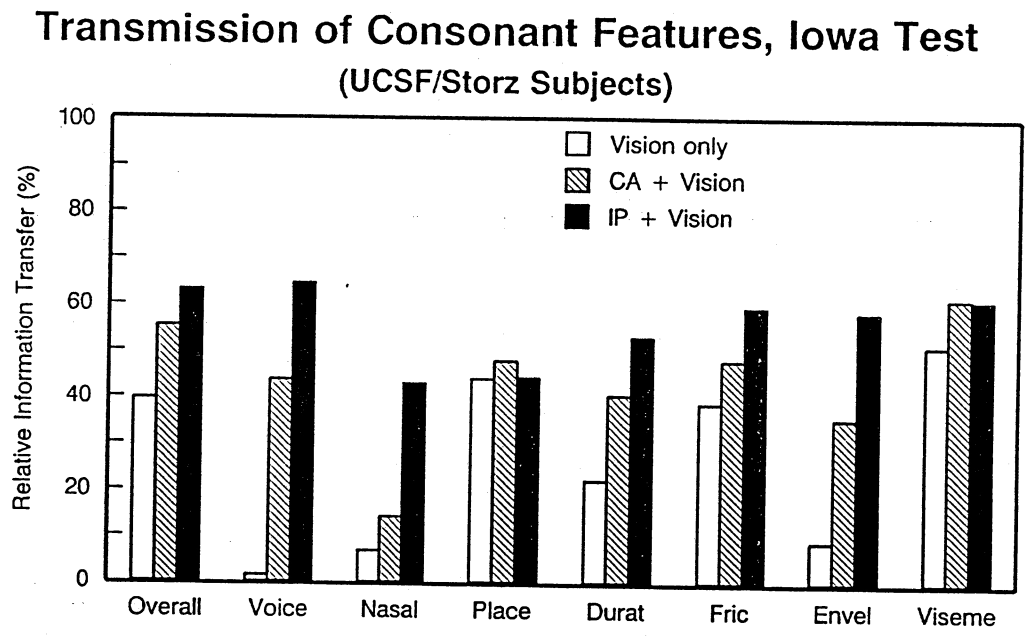

Fig. 3. Relative information transfer of speech features for the Iowa consonant test (videotape version), UCSF/Storz subjects.

speechreading alone [Owens and Blazek, 1985], and this ability is reflected in the choices for the viseme groupings. Thus, if subjects can distinguish the groups /p, b, m, f, v/, /ʃ, dʒ/, and /d, s, z, t, d, n, g, k/ through speechreading, then the scores for both viseme and place will be high.

Other features that exhibit some redundancy with the viseme groupings are duration and frication. The relatively high scores for these features with vision alone reflect this overlap. On the other hand, the scores for voicing, nasality, and envelope are all low for the vision-only condition. These features are invisible on the lips and have little or no redundancy with the viseme groupings.

The scores for both processor-plus-vision conditions demonstrate increases over the scores for the vision-only condition. Especially large increases are found for the features of voicing, duration, and envelope. In addition, the scores for overall information transfer are higher for the processor-plus-vision conditions.

Comparison of the scores obtained with the two processors indicates superiority of the IP processor for all features except place and viseme, where the scores are about the same. Scores for the IP processor are much higher for the features of voicing, nasality, and envelope.

The general finding of superior performance with the IP processor also is evident in the results from IT analysis of the RTI consonant matrices (/ð, s, z, t, d, n, k, l/, subjects 1-6). Results for the vision-only and processor-plus-vision conditions are presented in Fig. 4, and results for the

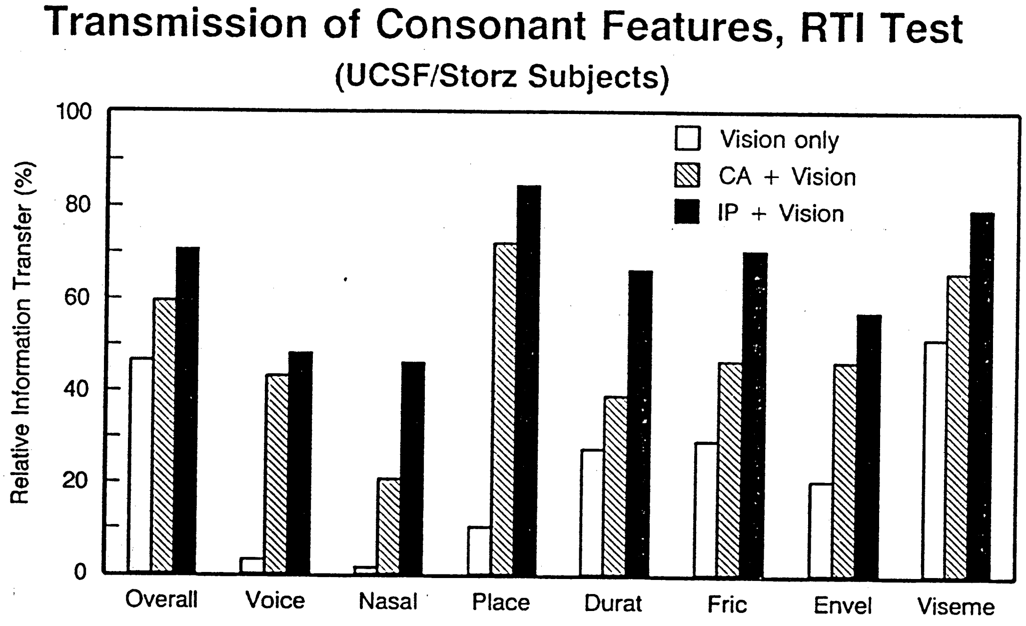

Fig. 4. Relative information transfer of speech features for the vision-only and vision-plus-processor conditions of the RTI consonant test, UCSF/Storz subjects.

processor-only conditions are presented in Fig. 5. In Fig. 4 the open, diagonally lined and solid bars again show IT scores for vision only, CA processor plus vision and IP processor plus vision, respectively. In Fig. 5 the stippled bars show IT scores for the CA processor only, and the vertically lined bars show the scores for the IP processor only.

For the conditions with a visual component (Fig. 4), high scores again are obtained for the viseme feature. Because the consonants in the RTI test all have a nonlabial place of articulation, however, high scores for the viseme feature merely show that the groups /s, z, t, d, n/, /k, l/, and /ð/ can be distinguished. /ð/ and /l/ usually are visible through tongue protrusion and tongue flap, respectively, even though they have nonlabial places of articulation. Perception of these cues for /ð/ and /l/ can produce relatively high viseme scores for the consonants in the RTI test.

Another effect of the choice of consonants for the RTI test is to hold place of articulation essentially constant. All consonants except /k/ have a mid place of articulation [Singh and Black, 1966]. Thus, the only distinction that has to be made to produce high place scores is the one between /k/ (back place of articulation) and the remaining consonants. The low place score for the vision-only condition in Fig. 4 reflects the fact that the place and viseme features are not redundant for the particular consonants of the RTI test. The scores for all other features (voicing, nasality, duration, frication, and envelope) are generally consistent with the scores for the vision-only condition of the Iowa videotape test.

Comparison of results across conditions again shows increases over the vision-only scores when either processor is used with speechreading. The largest increases are found for the features of voicing, nasality, place, and envelope. The increases for voicing and envelope are quite similar to those found for the Iowa test. The increases for nasality and place, however, are not seen (place) or not as large (nasality) in the Iowa results. The difference in the increases for place can be attributed to the particular choice of consonants in the RTI test, as outlined above. The difference in the increases for nasality is one of degree in that increases are found for both tests, but the relative increase for the CA processor plus vision over vision only is not as large for the Iowa test compared with the increase for the RTI test. This difference between tests again might be a consequence of the different choices of consonants: the only nasal in the RTI test is /n/, while the Iowa test contains /n/ and /m/.

As with the Iowa test, large increases are found in feature transmission scores when the IP processor is used instead of the CA processor for the vision-plus-processor conditions. The IP processor produces at least some increase in the score for every studied feature, and substantial increases are demonstrated for the features of nasality, duration, and frication. The same pattern of increases is evident in the scores for the Iowa videotape test; however, the relative increases for the voicing and envelope features are greater with the Iowa test, while the relative increases for the duration and frication features are greater with the RTI test. These differences probably can be attributed to the differences in the consonant sets and to test variability. In all, the patterns of results from the Iowa and RTI tests are remarkably consistent. Both patterns demonstrate substantial gains over vision alone when either processor is used in conjunction with speechreading, and both patterns show superiority of the IP processor. In addition, the particular differences in feature scores found between conditions for one of the tests usually are found for the other test as well.

The results from the RTI test for the processor-only conditions (Fig. 5) mirror those reviewed above for the processor-plus-vision conditions (Fig. 4). Specifically, the IP processor again produces an increase in the score for every studied feature, and substantial increases are found for the features of nasality, duration, and frication. Moreover, for all features the ratios of the scores for the CA-processor-plus-vision and IP-processor-plus-vision conditions (Fig. 4) closely approximate the ratios for the CA-processor-only and IP-processor-only conditions (Fig. 5). These findings suggest that the IP processor provides additional cues which are utilized by the subjects in both the hearing-only and hearing-plus-vision conditions.

In contrast to the results from the Iowa and RTI consonant tests, the IT scores from the RTI vowel test (/i, I, ɔ, o, u/, subjects 1-6) indicate superiority of the CA processor. These scores for the vowel test are presented in Fig. 6, where the coding of the bars for the various conditions is identical to the coding used in Figs. 3-5. Comparison of the IT scores between processors shows that the CA processor produces higher or equivalent scores for every feature. For the processor-plus-vision conditions higher scores are obtained for overall transmission, F1, and duration; and for the processor-only conditions higher scores are obtained for these features and

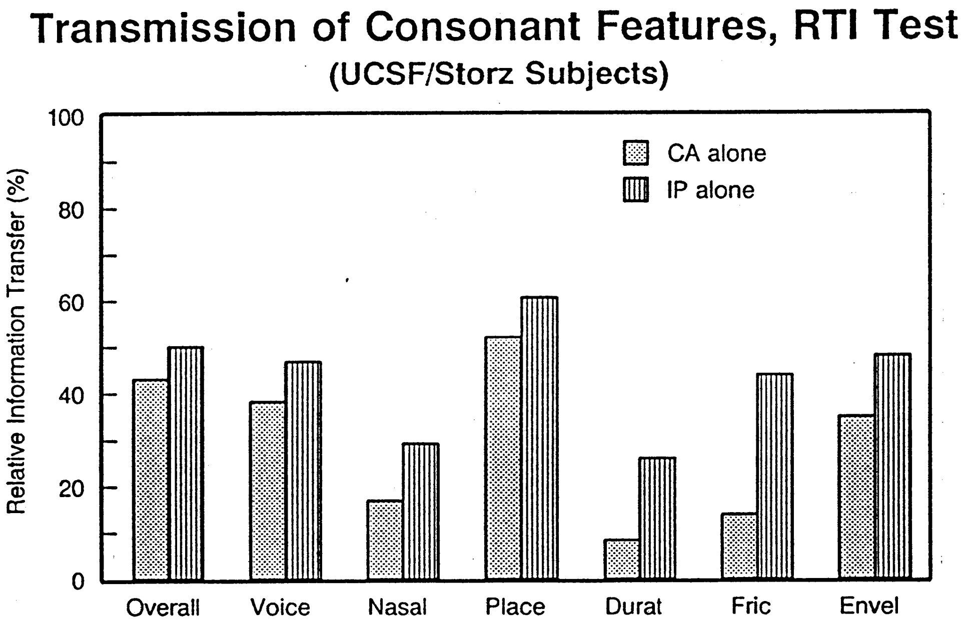

Fig. 5. Relative information transfer of speech features for the processor-only conditions of the RTI consonant test, UCSF/Storz subjects.

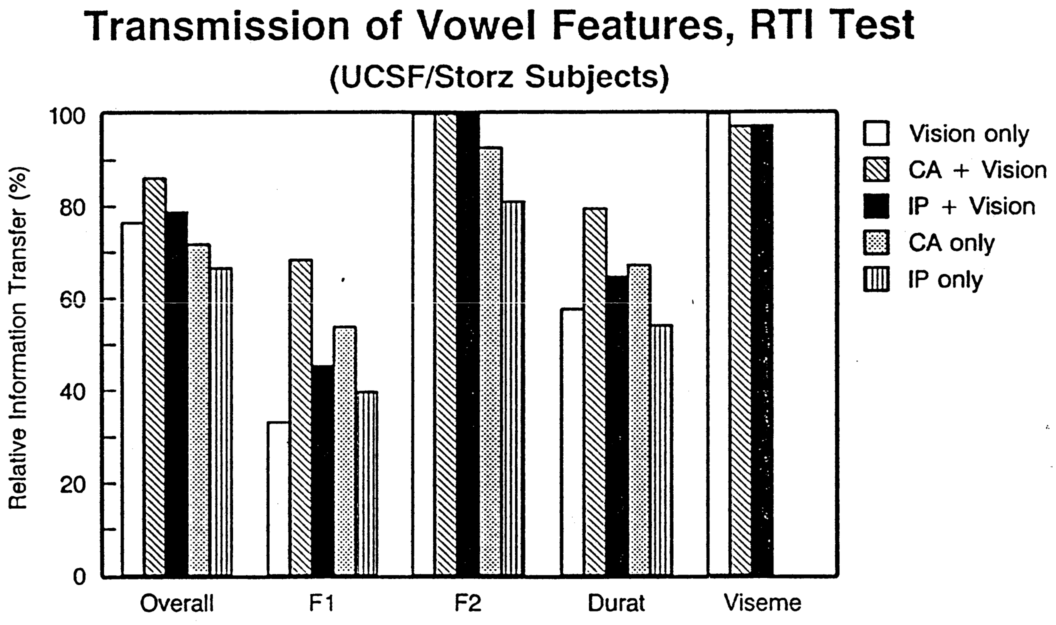

Fig. 6. Relative information transfer of speech features for the RTI vowel test, UCSF/Storz subjects.

F2. In the cases where equivalent scores are found (F2 and viseme features, processor-plus-vision conditions), ceiling effects may have masked true differences between the processors. A more difficult test (with, for example, more vowels and less redundancy between assignments for the F2 and viseme features) would provide a more sensitive detector of any difference between processors. In any event, the present results show that the CA processor is superior at least for the transmission of F1 and duration information.

The most general observations from the IT data reviewed above for the UCSF/Storz subjects are that (a) the IP processor produces higher or essentially equivalent scores for every studied feature of the phonemes in the Iowa and RTI consonant tests and (b) the opposite is found for every studied feature of the phonemes in the RTI vowel test.

Consonant and Vowel Identification, Symbion Subjects

Percent correct scores for the processors evaluated in tests with the Symbion subjects (subject 7 and 8) are shown in Figs. 7 and 8. As in all previous and subsequent figures, the stippled bars represent scores for the CA processor only; the bars with diagonal lines represent scores for the CA processor plus vision; the bars with vertical lines represent scores for the IP processor only; and the solid bars represent scores for the IP processor plus vision. All scores are from the combined results obtained with the male and female speakers of the Iowa videodisc tests.

Results from the tests with subject 7 (Fig. 7) show that large increases in identification scores for both vowels and consonants, with and without vision, are obtained when either of the IP processors is used instead of the subject's own CA processor. Scores for vowel identification with hearing alone increase from 55.5 percent correct with the CA processor to 67.0 and 85.0 percent correct with the two IP processors, and scores for consonant identification increase from 28.5 percent correct with the CA processor to 41.0 and 48.0 percent correct with the IP processors. The increases in the scores for consonant identification are consistent with the increases in those scores found for the UCSF/Storz subjects. The sizable increases in the scores for vowel identification, however, are quite different from the results for the UCSF/Storz subjects. As noted above, the UCSF/Storz subjects generally obtained higher scores on tests of vowel identification with the CA processor.

? Initial inhibitory effect via greater spatial selectivity

An additional aspect of the results presented in Fig. 7 is that the IP processor with the positive-leading pulses (Rb1b, last column) produced higher scores than the IP processor with the negative-leading pulses (Rb1a, middle column). This finding was counter to our expectation (based on Ranck, 1975, for instance) that the use of negative-leading pulses might improve the representation of speech signals via greater spatial specificity of neural excitation around the active electrodes.

Percent correct scores for subject 8 (Fig. 8) also demonstrate superior performance of the IP processor for consonant identification. The processors in Fig. 8 are arranged in an order of increasing scores of consonant identification with hearing alone. Note that all scores are high (ranging from 69.5 percent correct for the CA processor to 83.5 percent correct for the last IP processor) and that all variations of IP processors produce higher scores than the CA processor. Among the IP processors, scores for the six-

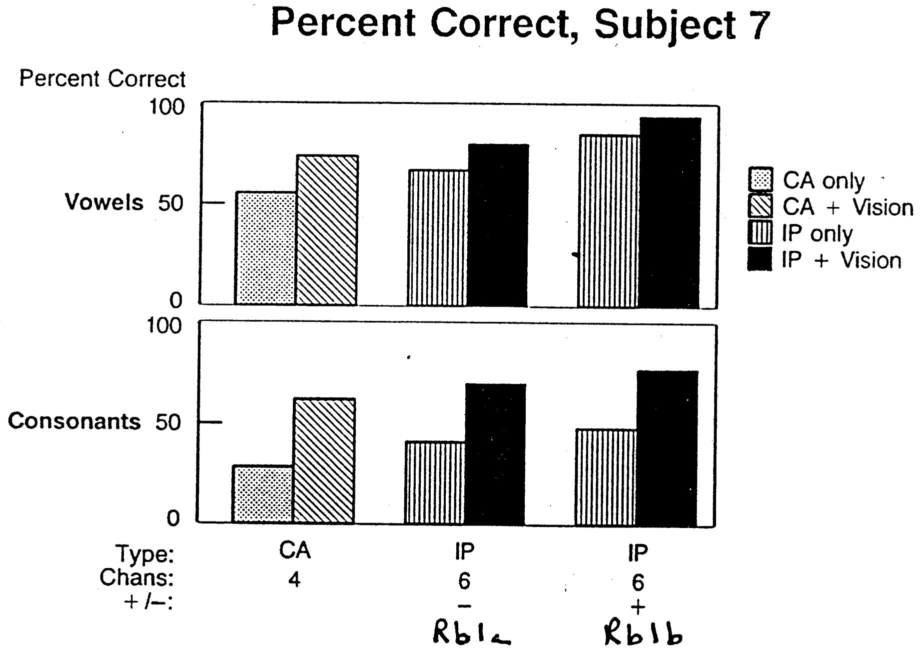

Fig. 7. Overall percent correct scores for tests of consonant and vowel identification, subject 7 (Symbion patient RB).

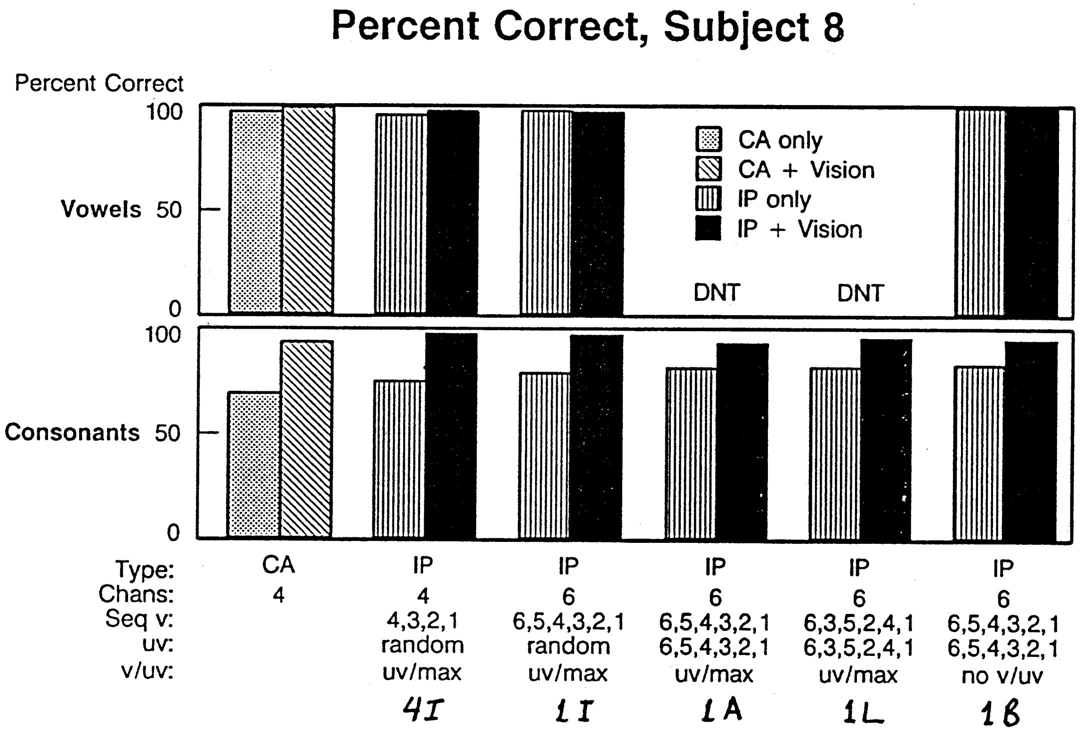

Fig. 8. Overall percent correct scores for tests of consonant and vowel identification, subject 8 (Symbion patient MP).

channel processors (79.5, 82.0, 82.5 and 83.5 percent correct) are somewhat higher than the scores for the four-channel processor (75.5 percent correct).

As is evident from Fig. 8, the tested variations of six-channel IP processors did not produce large changes in performance. However, the subject did report that the processor with an update order designed to produce the maximum spatial separation between sequentially-stimulated channels (1L) sounded "clearer" and "more intelligible" than the otherwise identical processor with a base-to-apex order (1A). In addition, he volunteered that the "maximum rate" processor (1B, no voiced/unvoiced coding) was the most intelligible among all tested variations of IP processors.

The remaining scores in Fig. 8 all approximate 100 percent correct. These scores therefore do not indicate superiority of any one processor over another.

Results from IT analyses consonant and vowel matrices from the studies with both Symbion subjects are presented in Figs. 9-11. Aggregate matrices submitted to IT analysis were compiled by combining the data obtained from the tests with male and female speakers for each condition. In addition, aggregate matrices for the IP processor were compiled by combining the data obtained from all variations of six-channel IP processors (processors Rb1a, Rb1b, 1L, 1A, 1L, and 1B).

Feature transmission scores for consonant identification with vision only and with vision plus speech processor are presented in Fig. 9. The pattern of results in Fig. 9 is almost identical to the pattern shown in Fig. 3 for the Iowa videotape test with the UCSF/Storz subjects. In particular, the scores for both processor-plus-vision conditions demonstrate large increases over the scores for the vision-only condition, and comparison of the scores for the two processors indicates clear superiority of the IP processor. As before, scores for the IP processor are much higher than those for the CA processor for the features of voicing, nasality, and envelope.

Results from IT analyses of consonant matrices from the processor-only conditions are shown in Fig. 10. As with the previous results from the RTI tests with the UCSF/Storz subjects (Fig. 5), increases in transmission scores are demonstrated for every feature when the IP processor is used instead of the CA processor. Here quite large increases are found for the Symbion subjects across all features except duration, where the increase is somewhat smaller. The relatively small increase in the score for duration is consistent with the relatively small increase in that score for the vision-plus-processor conditions shown in Fig. 9.

Finally, results from IT analyses of the vowel matrices are presented in Fig. 11. Because subject 8 scored close to 100 percent correct for all tests of vowel identification, ceiling effects would mask any true differences among processors for this subject. Therefore, the results for subjects 7 and 8 are shown in separate panels of Fig. 11. As expected, the IT scores for subject 8 approximate 100 percent for all features when any of the speech processors is used. For subject 7, though, a clear superiority of the IP processor is demonstrated in the IT scores. In particular, substantially higher scores are

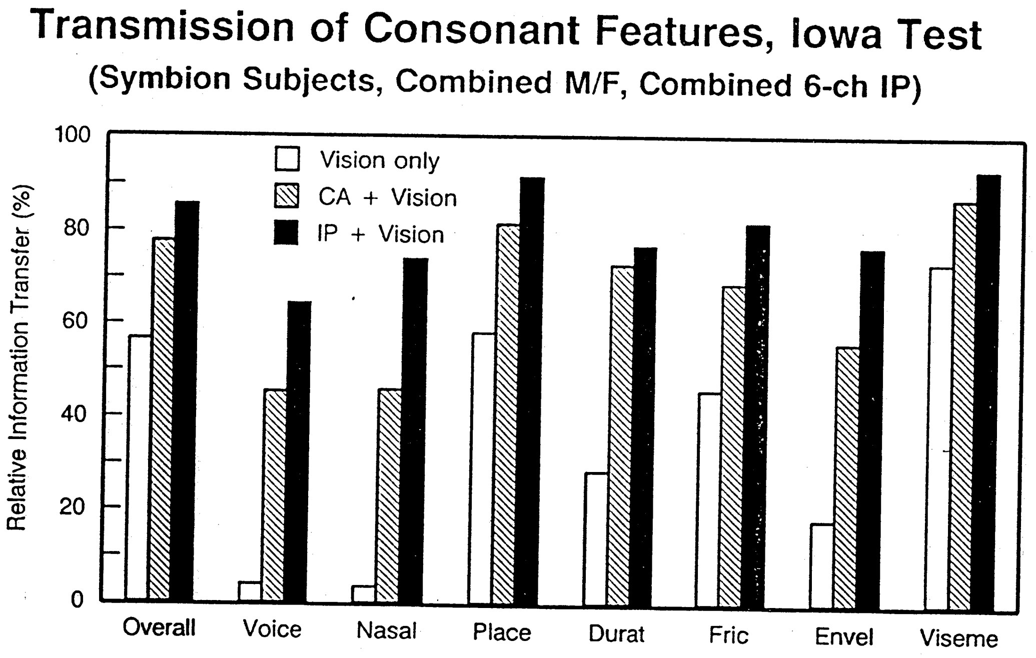

Fig. 9. Relative information transfer of speech features for the vision-only and vision-plus-processor conditions of the Iowa consonant test (videodisc version), Symbion subjects.

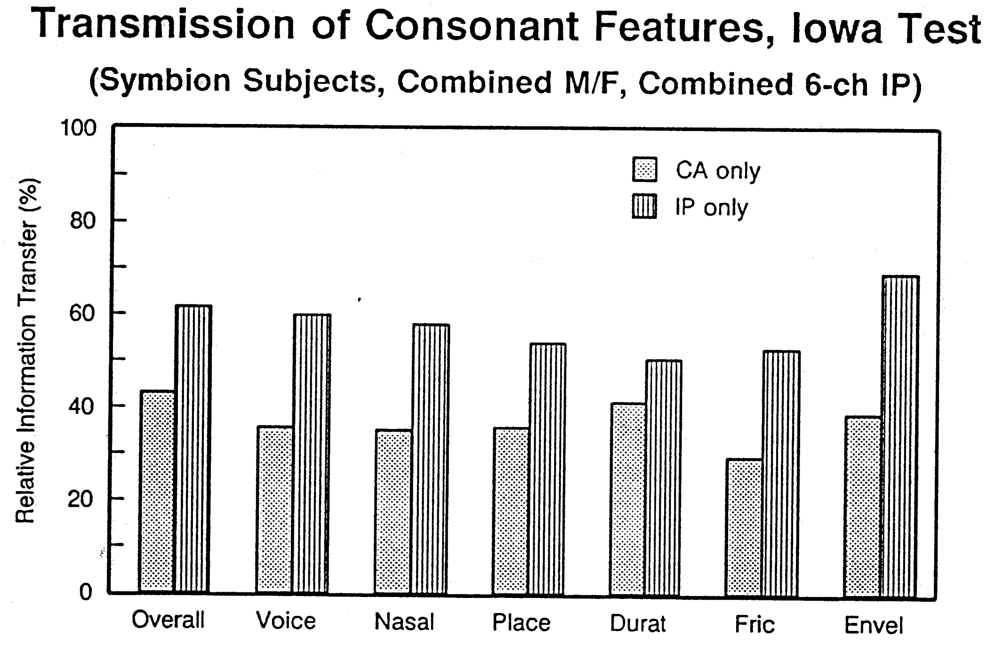

Fig. 10. Relative information transfer of speech features for the processor-only conditions of the Iowa consonant test (videodisc version), Symbion subjects.

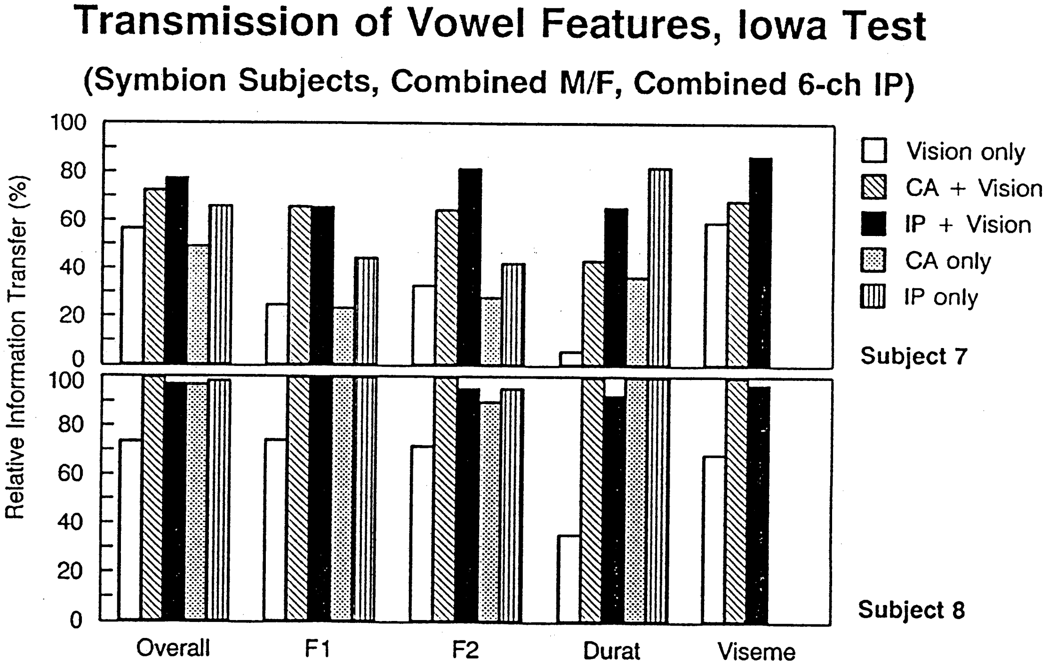

Fig. 11. Relative information transfer of speech features for the Iowa vowel test, Symbion subjects.

found for the features of F2 and duration when the IP processor is used in conjunction with speechreading, and substantially higher scores are found for those features and F1 when the IP processor is used without visual cues.

To summarize the IT results for the Symbion subjects, we note that (a) the IP strategy provides much higher transmission scores than the CA strategy for most consonant features, with and without vision, and (b) the IP strategy provides much higher transmission scores for all vowel features in the hearing-alone condition.

Results from Tests of Open-Set Recognition

The most difficult tests normally administered to assess the performance of patients with cochlear implants are tests of open-set recognition. Performance on these tests probably depends on a host of linguistic and cognitive skills that are not involved in tests of consonant and vowel identification. That is, the open-set tests help to evaluate the integration of segmental identification (consonants and vowels), prosodic cues and contextual information. The open-set tests thus provide complex measures of the representation of speech sounds at the auditory periphery and the interpretation of this representation in the central nervous system.

Results from the open-set tests of the MAC battery for the subjects and processors of this study are presented in Fig. 12. The tests include those of spondee recognition (Sp), recognition of monosyllabic words from Northwestern University list six (NU6), recognition of everyday sentences from lists prepared at the Central Institute for the Deaf (CID), and recognition of

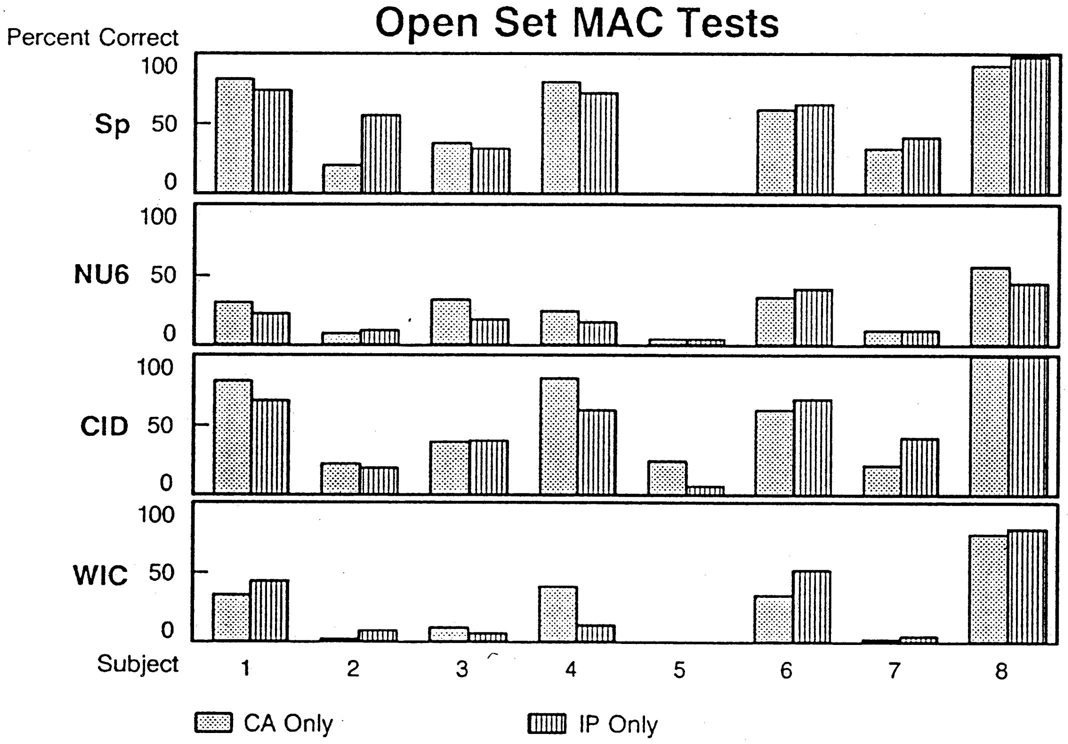

Fig. 12. Results from subtests of the MAC battery designed to measure open set recognition of speech. Abbreviations for the subtests are Sp for spondee recognition; NU6 for recognition of monosyllabic words from Northwestern University list 6; CID for recognition of everyday sentences from lists prepared at the Central Institute for the Deaf; and WIC for recognition of words in context. Subjects 1 through 6 are the UCSF/Storz subjects, and subjects 7 and 8 are the Symbion subjects.

single words in the context of sentences (WIC). Results presented for the IP processors for subjects 7 and 8 are those from processors Rb1a and 1L, respectively (see Table 2).

Comparison of the results across subjects for each of the open-set tests demonstrates that there are no significant differences between processors (paired t < 1.51 and p > .10 for all tests). However, substantial differences are found among subjects both in terms of overall performance and in terms of the scores for the two processors. Subjects 1, 4, 6 and 8 have excellent performance with both processors, while the remaining subjects have either moderate (subjects 2, 3 and 7) or poor (subject 5) performance with both processors. Between processors, subject 4 has higher scores with the CA processor for all four tests and subject 6 has higher scores with the IP processor for all four tests. Paired t comparisons between processors for these tests show that the CA processor is significantly better for subject 4 (paired t = 3.25; p < .05) and that the IP processor is marginally better for

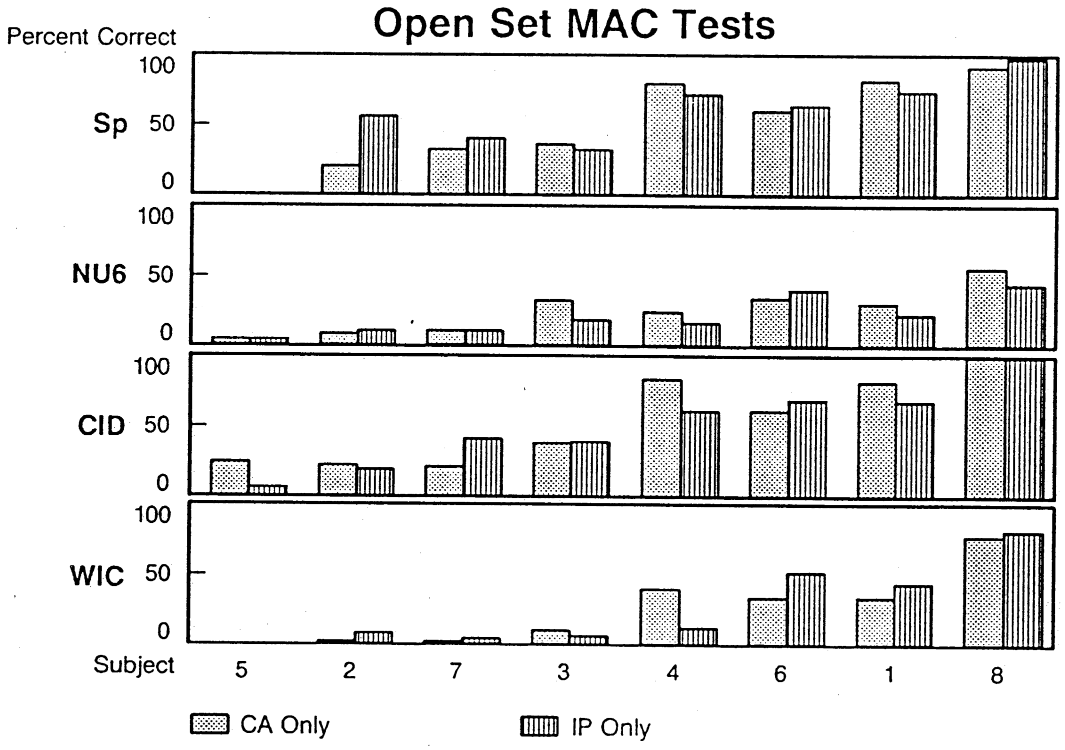

Fig. 13. Results from the open-set tests (see Fig. 12) arranged in a rank order of overall scores (average across tests) for each subject.

subject 6 (paired t = 2.90; p < .10). No significant differences are found between processors for the remaining subjects (paired t < 1.67; p > .10).

An additional aspect of the open-set results is illustrated in Fig. 13. In this figure the results are arranged in a rank order of overall scores for each subject. As is obvious from this ordering, subjects who obtained high scores with one processor also did well with the other and *vice versa*. Thus, patient variables must have played a major role in the measured outcomes for the prostheses and processors of the present studies.

Discussion

In the studies reviewed in this report, the CA and IP processors were compared in tests with six subjects implanted with the UCSF/Storz electrode array and with two subjects implanted with the Symbion electrode array. The tests included those of consonant and vowel identification and of open-set recognition.

Large differences between processors were demonstrated in the results from the consonant and vowel tests. The IP processor produced superior results for consonant identification, with and without the addition of visual cues, for both sets of subjects. However, the increases in IT scores for consonant features were generally greater for the Symbion subjects.

In contrast to the consonant results, superiority in tests of vowel identification was split between the two processors for the two sets of subjects. The CA processor produced superior results for the UCSF/Storz subjects, while the IP processor produced superior results for Symbion subject 7 (subject 8 obtained perfect or nearly perfect scores for both processors).

The relatively large gains in performance obtained with IP processor for the Symbion subjects may have been produced by more optimal fittings of that processor compared to those for the UCSF/Storz subjects. Specifically, the percutaneous connector of the Symbion prosthesis allowed the use of short-duration pulses and up to six channels of intracochlear stimulation. In contrast, limitations of the transcutaneous transmission system for the UCSF/Storz subjects both restricted the number of channels to four or fewer and precluded the use of short-duration pulses.

Although results from the consonant and vowel tests indicated clear differences between the CA and IP processors, results from the open-set tests did not demonstrate an overall superiority of one processor over the other. This latter finding is a little surprising in that consonant identification in particular usually is directly related to speech intelligibility [see, e.g., Denes, 1963; Miller and Nicely, 1955; Minifie, 1973]. Thus, in the absence of other factors, one might expect that the IP processor would produce superior scores on the open-set tests. However, other factors may have affected the present results. These factors might include (a) the huge disparity in the subjects' experience with the two processors and (b) the fact that good performance on the open-set tests probably involves a host of linguistic and cognitive skills that are not tapped in tests of consonant and vowel identification.

The one of these factors that may have favored one processor over the other is the disparity in experience. For the subjects of this study, experience with the CA processor approximated 1 year of daily use, while experience with the IP processor was limited to the tests conducted with that processor (among several) during a 1-week period. As mentioned before, many previous studies have demonstrated large learning effects associated with the experience gained from using a prosthesis system. To the extent that such learning is not transferred to a new system (in this case, a new speech processor) [Dowell et al., 1987; Tyler et al., 1986], one might expect the disparity in experience to influence test scores in favor of the CA processor. In any event, equivalent or superior results on the open-set tests are found with the IP processor for seven of the eight subjects in the present study. This finding suggests (a) that the IP processor could be applied to these seven subjects without any initial deficit and (b) that, with equivalent experience, the IP processor might emerge as the superior processor for most subjects.

Conclusions

Major conclusions from the results presented in this report include the following:

1. Differences among subjects account for a large proportion of the variance when the CA and IP processing strategies are compared with tests of open-set recognition.

2. However, individual performance can be highly sensitive to the choice of strategy, as measured either with tests of phoneme identification or open-set recognition.

3. The IP strategy generally provides superior identification scores, and may ultimately provide superior open-set scores, for a large majority of implant patients.

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III. Plans for the Next Quarter

Our plans for the next quarter include the following:

1. Initiation of studies with recipients of brainstem implants, in collaboration with R.V. Shannon and J. Wygonski of the House Ear Institute.

2. Follow-up studies with Nucleus patient SW, to begin speech perception studies with her.

3. Follow-up studies with Symbion patient MP, to evaluate additional variations of the "maximum rate" IP processor mentioned in section II of this report.

4. Completion of a TMS320C25-based bench processor, for real-time implementation of advanced IP processor designs.

5. Presentation of project results in an invited lecture at the University of Iowa (August 28) and at the 20th Annual Neural Prosthesis Workshop (October 18-20).

6. Hold a project site visit at Duke for Drs. Hambrecht and Heetderks (October 12).

7. Continue work on manuscripts in progress.

APPENDIX

Summary of Reporting Activity for the Period of May 1 through July 31, 1989

NIH Contract N01-DC-9-2401

Wilson, B.S.: Within patient evaluation of speech processors. Invited paper presented at the Engineering Foundation Conference on Implantable Auditory Prostheses, Potosi, MO, July 30 to August 4, 1989.

Finley, C.C.: Electric field patterns produced by intracochlear stimulation. Poster presentation at the Engineering Foundation Conference on Implantable Auditory Prostheses, Potosi, MO, July 30 to August 4, 1989.