RESEARCH TRIANGLE INSTITUTE

TECHNICAL PROPOSAL

Speech Processors for Auditory Prostheses

Submitted in response to NIH RFP No. NIH-NINCDS-88-04

April 18, 1988

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CONTENTS

I. Introduction

The Research Triangle Institute (RTI) is pleased to submit this proposal in response to RFP No. NIH-NINCDS-88-04, "Speech Processors for Auditory Prostheses." In this proposal we will review results and achievements from our current project supported by the Neural Prosthesis Program (NIH project N01-NS-5-2396, same title as above), and we will outline our plan for continued work. The plan for continued work includes efforts directly related to (a) further development of a laboratory-based speech processing system, (b) evaluation of different speech processing techniques in tests with implanted human subjects, and (c) design and fabrication of wearable speech processors.

II. Background

In this section we will present reviews of the major activities and studies of our current project. These activities and studies touch on many areas related to the design and evaluation of speech processors for auditory prostheses. In particular, we will describe our work to (a) compare analog and pulsatile coding strategies for multichannel cochlear prostheses; (b) design and evaluate a two-channel, "Breeuwer/Plomp" processor; (c) characterize aspects of pitch and loudness perception with cochlear implants in directed psychophysical studies; (d) develop and apply a wearable speech processor for multichannel auditory prostheses; and (e) collaborate with investigators at the University of California at San Francisco (UCSF) in the development of the speech processor and transcutaneous transmission system for a next-generation auditory prosthesis. In addition to the descriptions of these activities, we will outline other important collaborations we have established during the course of our current project, and we will describe our experience with different types of implant patients.. A review of key studies conducted in our previous "speech processors" project for the Neural Prosthesis Program (NIH project N01-NS-3-2356) is presented in this proposal as one of the supporting documents (section X.D).

II.A. Direct Comparisons of Analog and Pulsatile Coding Strategies

The design of speech processors for cochlear prostheses is a multifaceted activity. At the most basic level such processors must extract or preserve from speech those parameters that are essential for intelligibility and then encode those parameters for electrical stimulation of the auditory nerve. Areas of knowledge necessary to the informed design of speech processors for cochlear prostheses include electrical engineering and the speech and hearing sciences. The range of options for processor design is quite large, and this latitude is reflected in the many approaches that have been taken in the design of clinically applied devices (Millar *et al.*, 1984; Moore, 1985; Parkins, 1986; Pfingst, 1986).

A remarkable finding from evaluations of these approaches is that each of several distinctly different processing strategies can produce high levels of speech perception in some patients. Unfortunately the converse is also true, in that poor levels of performance are found for other patients using the same strategies. This heterogeneity of outcomes may result from differences among patients in (a) patterns of nerve survival in the cochlea; (b) the integrity of the central auditory pathways; or (c) cognitive ability and language acquisition. The likely influence of patient variables on outcome obviously complicates comparisons aimed at identifying the best types of electrode and speech processor designs for cochlear prostheses. Indeed, such comparisons are not meaningful when small populations of subjects are used for the evaluation of each system, or when test procedures used at the various laboratories involved in the evaluation of individual systems are different.

Recognition of the problem just described helped to initiate two major studies in which relatively large populations of patients implanted with different devices will be tested in a uniform and consistent manner. One of these studies is a cooperative effort among VA medical centers (N. Cohen, PI) and the other study is being conducted at the University of Iowa (B. Gantz, PI; see Gantz, 1987 and Gantz *et al.*, 1987). Results from these studies should be of great value in establishing expected levels of performance for contemporary cochlear prostheses.

A complementary method for the comparison of prosthesis systems is to evaluate different processing strategies and electrode coupling configurations in tests with individual implant patients. An important advantage of such tests with individual patients is that controls are provided for patient variables. Thus, for a given patient with a fixed pattern of nerve survival and fixed levels of cognitive skill, etc., the performance levels of different speech processors can be directly compared.

In recent studies conducted in collaboration with investigators at UCSF and Duke University Medical Center (DUMC), our team has compared a wide variety of processing strategies in tests with each of eight patients implanted with the UCSF/Storz electrode array. 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. To emphasize how the design of the processor can affect the outcome for individual patients, we will restrict ourselves here to brief descriptions of tests related to these two types of processor. Detailed descriptions of these tests, along with the results obtained with other processing strategies, are presented elsewhere (Wilson et al., 1985; 1986; 1987b; 1988a; 1988b; 1988c).

Processing Strategies

In the clinical UCSF/Storz device alternate pairs of electrodes are stimulated simultaneously with the compressed analog outputs of a four-channel speech processor. The basic functions of this processor are to compress the wide dynamic range of input speech signals onto the narrow dynamic range available for electrical stimulation of the cochlea, and then to filter the compressed signal into individual frequency bands for presentation to each pair of stimulated electrodes. Typical waveforms of the CA processor are shown in Fig. II.A-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 4 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. II.A-1 thus exemplify differences in waveforms for voiced and unvoiced intervals of speech.

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 frequency of the vowel during the voiced interval, and the lack of periodicity in the output of any channel reflects the noise-like quality of the "T" during the unvoiced interval. As has been described elsewhere (Schindler and Kessler, 1987; Schindler et al., 1986a; 1986b; 1987; Wilson et al., 1988c), this

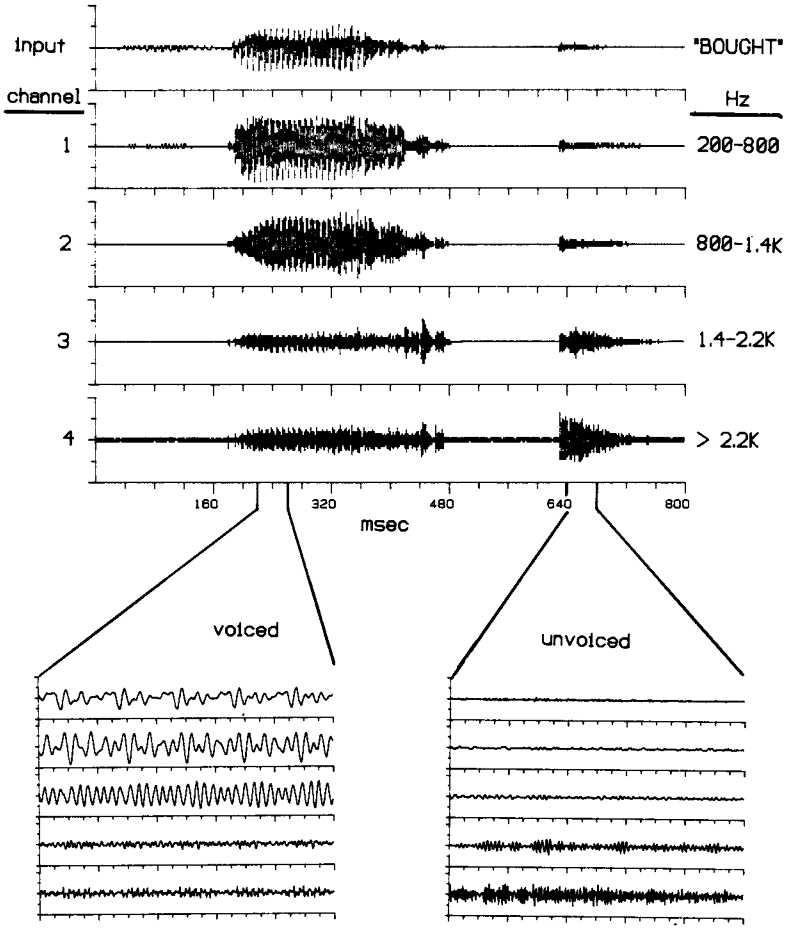


Fig. II.A-1. Waveforms of a compressed analog (CA) processor.

representation of speech features can support high levels of recognition and understanding for many (but not all) of the patients implanted with the UCSF/Storz prosthesis.

To introduce the design of the IP processor, we note that it is intended to solve a potentially serious difficulty with multichannel CA processors -- the problem of channel interactions. Simultaneous stimulation of more than one channel with continuous waveforms results in summation of the electric fields from the individual bipolar pairs of 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, 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. II.A-2 through the use of nonsimultaneous stimuli. There is no temporal overlap between the stimulus pulses so that direct summation of electric 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 processor stimulation cycles are timed to begin 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. II.A-2.

Comparison of Figs. II.A-1 and II.A-2 shows large differences in the stimuli presented for the CA and IP processing strategies. One might expect that the CA processing strategy would provide the greatest benefits to patients who could appreciate details in the stimulus waveforms (see discussion below) and who have low thresholds of stimulation. In contrast, the IP processing strategy might be expected to provide superior performance for less fortunate patients who cannot appreciate such details in CA stimulus waveforms and who have high thresholds of stimulation. We note that high thresholds of stimulation and high levels of measured channel interactions with simultaneous stimuli are both regarded as signs of poor nerve survival in the implanted ear (Gardi, 1985; Merzenich et al., 1978; Pfingst and Sutton, 1983; White et al., 1984). Thus, application of an IP

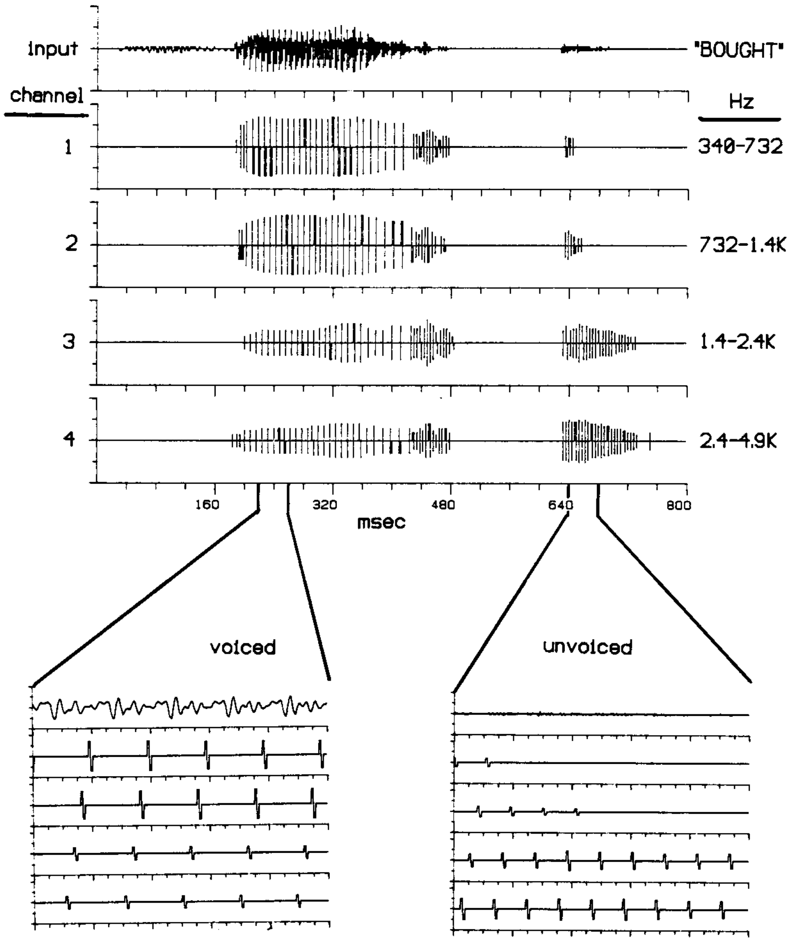


Fig. II.A-2. Waveforms of an interleaved pulses (IP) processor.

processor may confer special benefits for patients with poor nerve survival.

Methods

All eight patients participating in our studies had been implanted with the UCSF electrode array. The first two patients were fitted with percutaneous cables and the remaining six with the four-channel transcutaneous transmission system (TTS) of the UCSF/Storz prosthesis. Use of the cable allows direct access to all 16 electrode contacts in the array (usually configured as eight bipolar pairs) and direct control over the current or voltage waveforms of the stimuli. In contrast, alternating bipolar electrode pairs are assigned to the four channels of the TTS, and the current and voltage waveforms are complex functions of the nonlinear impedances of the electrodes and the limited frequency response of each TTS channel.

Because the cable allowed a much greater degree of stimulus control, many different processing strategies were evaluated in the studies with the first two patients (LP and MH). The performance of each strategy was measured with confusion matrix tests. The confusion matrix for vowels included the tokens "BOAT," "BEET," "BOUGHT," "BIT," and "BOOT," and the confusion matrix for consonants included the nonsense tokens "ATA," "ADA," "AKA," "ASA," "AZA," "ANA," "ALA," and "ATHA." The tokens in the vowel matrix were selected to measure the ability to perceive differences in the formant frequencies of the vowels, and the tokens in the consonant matrix were selected to measure the ability to distinguish the nonvisible consonants that have the greatest frequency of occurrence in spoken English (Schubert, 1985).

Among the processing strategies evaluated with these first two patients, the IP approach achieved the best results. To assess further the performance of this strategy vis à vis the standard CA strategy of the UCSF/Storz prosthesis, an extensive series of standard tests was designed for the remaining six patients (all of whom were fitted with the TTS). In addition to the vowel and consonant confusion tests just outlined, this series included: all subtests of the Minimal Auditory Capabilities (MAC) battery (Owens _et al._, 1985); the Diagnostic Discrimination Test (DDT) of consonant confusions (Grether, 1970); connected discourse tracking with and without the prosthesis (De Filippo and Scott, 1978; Owens and Raggio, 1987); and the Iowa test of medial consonant identification with lip-reading cues (Tyler _et al._, 1983). In this proposal we will review briefly the results from the vowel and consonant confusion tests for all patients, and from the MAC and Iowa tests for the six patients fitted with the TTS. Results for the various patients will be compared for each individual test. Because of the highly varied nature of the MAC subtests, any attempt to analyze performance across tests would necessarily involve arbitrary assumptions about the relative weights of the subtest results. Detailed reports of the evaluation studies are available elsewhere (Wilson *et al.*, 1985; 1986; 1987b; 1988a; 1988b; 1988c).

Results for Patient LP

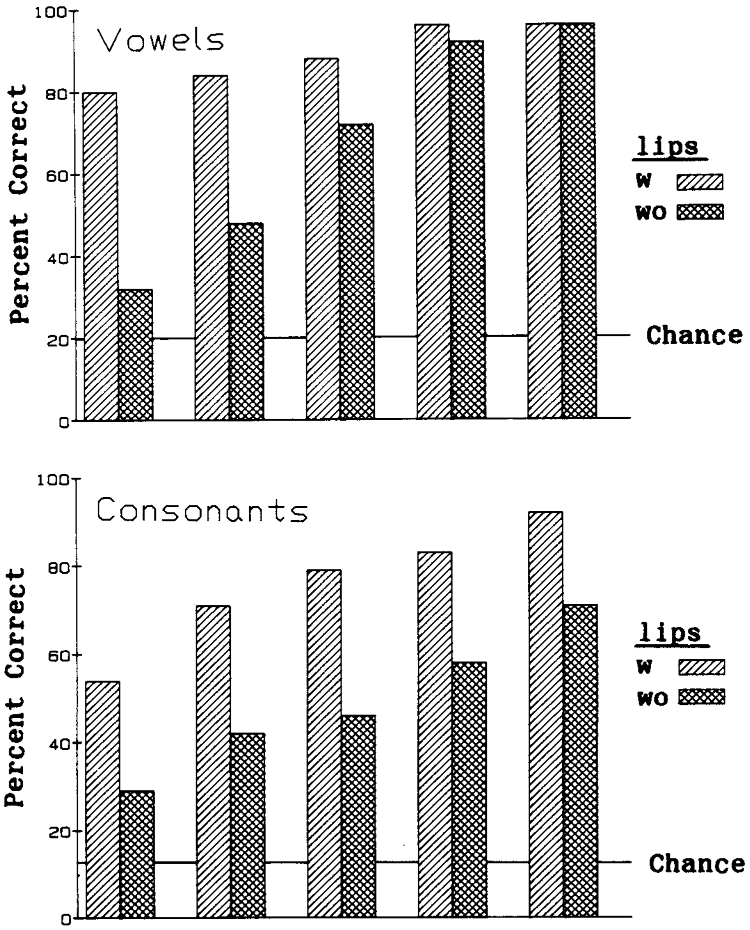
The first patient (LP) had a most discouraging picture of psychophysical performance. He had extremely severe channel interactions and high thresholds for bipolar electrical stimulation. His case was further complicated by extraordinarily narrow dynamic ranges and lability of thresholds and loudness levels both within and between testing sessions. LP's psychophysical findings of severe channel interactions, high thresholds and narrow dynamic ranges were all consistent with a picture of very poor survival of neurons in his implanted ear (Gardi, 1985; Merzenich *et al.*, 1978; Pfingst *et al.*, 1985; Pfingst and Sutton, 1983; White *et al.*, 1984; Wilson *et al.*, 1988a).

As might be expected, LP received no benefit from the CA processor used in the standard UCSF prosthesis. Indeed, he refused to describe any of the percepts produced with this processor as speech-like.

The first application of a 6-channel, IP processor immediately moved LP into the speech mode of auditory perception (Wilson *et al.*, 1985; 1988a). Of the eleven speech tokens initially presented to LP using the IP processor, seven were spontaneously recognized as the correct words or syllables. Although his performance declined when the number of channels was reduced from 6 to 4, formal tests with vowel confusion matrices indicated that LP could perform at a level significantly above chance ($p < 0.01$) even with a reduced 4-channel version of the IP processor (Wilson *et al.*, 1985). A medical complication required surgical removal of LP's implant, ending our study of him with these very encouraging preliminary results.

Results for Patient MH

With the second patient we were able to evaluate differences in processor performance in much greater detail. This patient also had psychophysical manifestations of poor nerve survival (Wilson *et al.*, 1986; 1988a). The results presented in Fig. II.A-3 show her levels of performance



Proc:	CA	IP	IP	IP	IP
Chans:	4	4	4	6	6
FO, v/uv?	NA	N	Y	N	Y
Overall %	49	61	71	83	89

Fig. II.A-3. Results of vowel and consonant confusion tests for patient MH. Diagonally-hatched bars indicate results obtained with lipreading and cross-hatched bars indicate results obtained without lipreading. The table at the bottom of the figure indicates the type of processor used (abbreviations are CA for "compressed analog" and IP for "interleaved pulses"); the number of stimulation channels; whether voicing information was explicitly coded for the IP processors; and the overall percent-correct scores from the four test conditions for each processor. The horizontal line in each panel shows the level of chance performance for that test. All of the scores are significantly above chance at the $p < 0.01$ level, except those for the compressed analog processor tests without lips.

in tests of vowel and consonant recognition. The diagonally hatched bars show her performance with lipreading, and the cross-hatched bars without. The chance levels of performance are indicated by the horizontal lines in each panel. Different processors are represented by different sets of bars. The characteristics of each processor are indicated in the labels at the bottom. For example, the leftmost set of bars shows the scores for a 4-channel CA processor. The remaining sets of bars show the scores for four variations of IP processors. These variations were produced by manipulating (a) the number of stimulation channels and (b) the way in which the beginnings of stimulus sequences were timed. In one approach stimulation cycles were timed to start in synchrony with the fundamental frequency for voiced speech sounds and at randomly-spaced intervals during unvoiced speech sounds. This constituted explicit coding of fundamental frequency and voiced/unvoiced distinctions. In the other approach stimulation cycles were timed to follow each other as rapidly as possible, providing no explicit coding of voicing information. In all, the results shown in Fig. II.A-3 allow direct comparisons of (a) a 4-channel CA processor vs. a 4-channel IP processor; (b) 4- vs. 6-channel IP processors; and (c) IP processors with and without explicit coding of voicing information. The comparisons indicate that:

1. Performance is markedly improved when a 4-channel IP processor is used instead of a 4-channel CA processor;

2. Scores are <u>much</u> higher in all categories except vowel identification with lipreading (where scores are about the same) when a 6-channel IP processor is used instead of a 4-channel IP processor; and

3. Explicit coding of voicing information improves the performance of IP processors, particularly in the categories of vowel identification without lipreading (4-channel processor), consonant identification without lipreading (6-channel processor) and consonant identification with lipreading (both processors).

Good test/retest reliability was thoroughly demonstrated for MH. When retested with a processor that had produced low scores on a previous occasion, MH always would obtain low scores again, and when repeating a test with a processor that earlier had performed well she always would repeat her high scores. The standard deviation of overall percent correct scores from seven repeated trials of the last (rightmost) processor shown in Fig. II.A-3, for example, was slightly less than three percent. All scores presented in Fig. II.A-3 are significantly above chance ($p < 0.01$) except for those of the two hearing-alone conditions for the CA processor.

Results for Patients Fitted with the TTS

The studies with the two percutaneous cable patients demonstrated that (a) different processing strategies can produce widely different outcomes for individual patients and (b) IP processors are far superior to the tested alternative processors for at least two patients with psychophysical signs of poor nerve survival. With these observations in mind, we were most interested in comparing the IP and CA strategies in extensive tests with a larger population of patients. We wondered, for example, how the IP processor would perform for successful users of a CA processor, and whether the potential advantages of the IP processors could be realized in patients with four or fewer channels of stimulation.

As mentioned above, six patients fitted with the 4-channel UCSF/Storz TTS participated in the follow-up studies. Each patient 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 confusions, and (c) the best of these IP processors was further evaluated using a broad spectrum of speech tests.

Before presenting the results obtained from the evaluations of the CA and IP processors, it is important to note several factors that favored the CA processor in comparisons of processor performance. First, all six patients entered our studies with substantial experience using the CA processor. We expected that the learning effects of such experience would strongly favor the CA processor in the comparisons (further discussion on this point is presented in Dowell et al., 1987; Tyler et al., 1986; Wilson et al., 1988c). In a typical case, experience with the CA processor would approximate one year of daily use, while experience with the real-time implementation of the IP processor would be between 15 and 30 minutes before formal testing. Therefore, the information provided by an IP processor would have to be immediately accessible to the patient in order for the results to be at all comparable to those obtained with the CA processor.

An additional factor weighing against the IP processor in these performance comparisons was the use of the 4-channel TTS. The principal limitations of that system for IP processors are (a) inadequate levels of voltage compliance for stimulation with short-duration pulses, (b) the small number of channels, and (c) lack of current control in the stimulus waveforms. Half of the patients in this study were further limited by having even fewer than four functional channels available for stimulation.

The loss of one or two channels in each of these cases has been attributed to fluid or particulate contamination admitted to the connector assembly of the implanted portion of the TTS during surgery (Schindler et al., 1986b). Although the problem of contamination has since been solved by modifying the surgical procedure, most of these six patients were implanted before the problem was evident and before these revisions had been made.

Extensive evaluation (with patient MH; see Wilson et al., 1986; 1988a) of variations in performance with parametric manipulations among IP processors suggested the following five criteria for fitting such designs, in approximate order of decreasing importance:

1. Total number of channels (large increases in performance are found when the number of channels is increased from 2 to 4 and from 4 to 6);
2. Number of channels updated per stimulation cycle, if fewer than the total number of available channels (performance in tests of consonant identification declines precipitously if the number of updated channels falls below 4);
3. Total duration of each stimulation cycle (performance gets better as duration is decreased, and is markedly better when the duration is less than 4-5 msec);
4. Time between sequential pulses (performance improves as the time between pulses is increased, up to the point at which the total duration of the stimulation cycle begins to exceed 4-5 msec); and
5. Explicit coding of voicing information (performance is better with explicit coding of voicing information, and the percepts elicited with processors that use such coding generally are described as more natural and speech-like).

Notice that the small number of channels and limited voltage compliance of the TTS place severe restrictions on meeting criteria 1-4 above. Also, the lack of current control introduces distortions in stimulus waveforms that may require greater separation of pulses in order to avoid channel interactions.

The parameters selected for the IP processors of these six TTS patients are presented in Table II.A-1. The best fulfillments of the five criteria were obtained for patients HE and MC2. Each had the use of all four

TABLE II.A-1. Parameters of Real-Time IP Processors.[a]

patient	channels	pulse widths/ phase (msec)	pulse sep. (msec)	cycle time (msec)
MC1	3	0.5	0.5	4.5
HE	4	0.5	0.5	6.0
JM	3	1.0	0.1	6.3
RC	2	0.5	0.1	2.2
ET	4	1.0 1.0 0.5 0.5	0.1	6.4
MC2	4	0.3 0.7 0.3 0.3	0.5	5.2

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

stimulation channels and the time between sequential pulses was a relatively long 0.5 msec for both patients. In addition, the stimulation cycle time for MC2 was almost within the 5.0 msec criterion for this parameter.

In contrast, relatively poor sets of parameters had to be used for the remaining patients. Patients MC1 and JM had only three usable channels and patient RC only two. The cycle times remained excessive for patients JM and ET, even with the times between pulses compromised down to only 0.1 msec.

The results of processor comparisons are presented in Figs. II.A-4 to II.A-8. Fig. II.A-4 shows performance levels for the tests of vowel and consonant identifications. Solid black bars represent the scores for lipreading alone, dotted bars for the CA processor alone, and cross-hatched bars for the CA processor with lipreading. Vertically-lined bars represent the scores for the IP processor alone and horizontally-lined bars for the IP processor with lipreading. Chance levels of performance are indicated by the horizontal lines in each panel and, as is the case in subsequent figures, any results that do not significantly exceed chance are noted in the figure captions.

Performance in the tests of vowel identification is quite high for both processors. All patients have scores of 80% correct or better for both processors with lipreading and 68% or better without lipreading. The means of the results for the two processors are not significantly different for either condition.

In contrast to the apparent equivalence of processors for the vowel test, the scores for the consonant test without lipreading are significantly higher for the IP processor ($p < 0.05$, paired t test). All patients except JM obtained higher scores using the IP processor for this condition. The difference between the means for the "with lipreading" condition is not significant. Analysis of specific confusions across patients for the two processing strategies is under way and will be presented elsewhere.

An indication of superior consonant recognition with the IP processor is also seen in the results for the Iowa test of medial consonant identification with lipreading cues. These results are presented in Fig. II.A-5. Every patient except MC2 has substantially higher scores with the IP processor. However, the difference in the means of the results for the two processors is not statistically significant. It is important to note that our procedure for administering this test was designed to confer any benefits of learning on the CA processor. The order of testing was to measure performance first with the IP processor plus lipreading, then with lipreading alone, and finally with the CA processor plus lipreading.

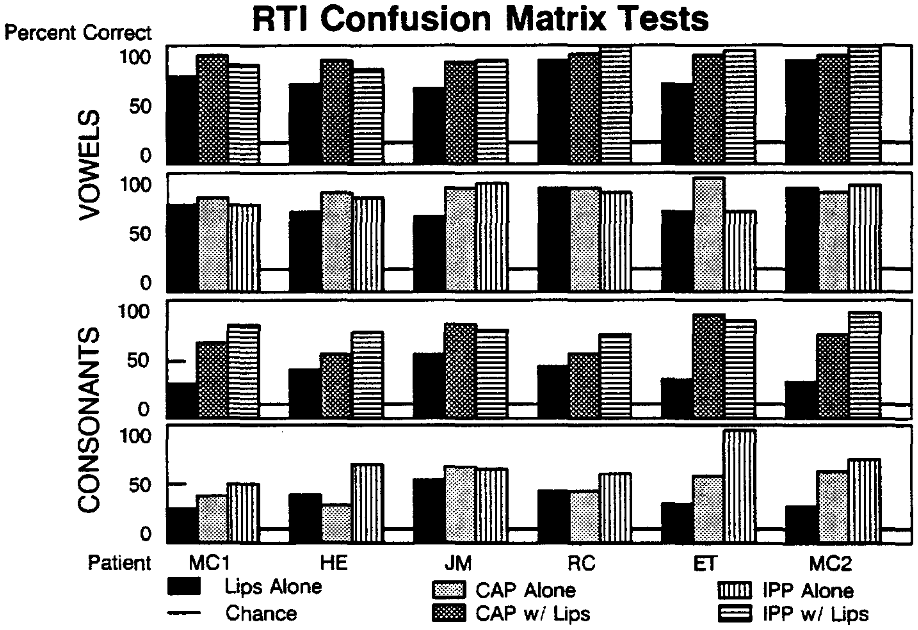


Fig. II.A-4. Results of vowel and consonant confusion tests for six patients fitted with the 4-channel UCSF/Storz transcutaneous transmission system. All of these scores are significantly above chance at the $p < 0.01$ level, except for some scores for the consonant tests with lips alone.

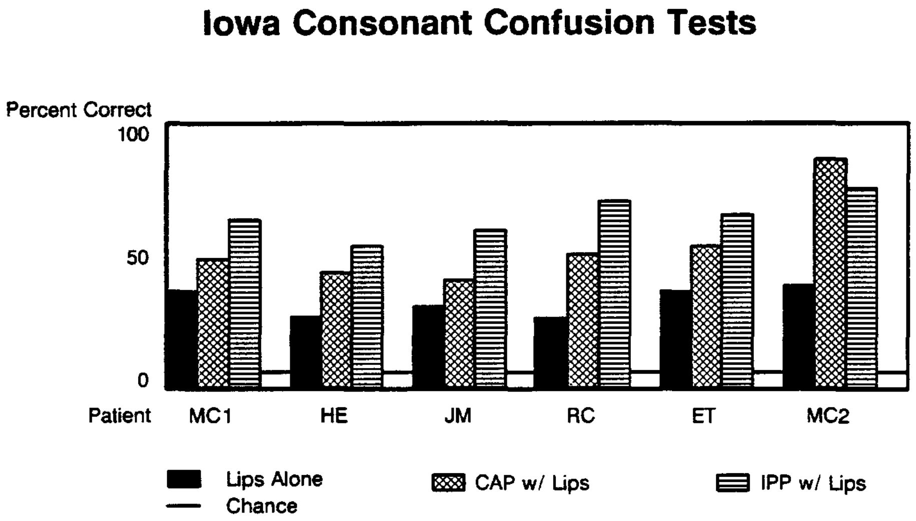


Fig. II.A-5. Results from the Iowa test of medial consonant identifications with lipreading cues. The patients are those described in the caption of Fig. II.A-4. All of these results are significantly above chance at the $p < 0.01$ level.

In addition to paired t tests, a Wilcoxon test (see Hollander and Wolfe, 1973) of nonparametric ranking of results across the six patients was applied to all measurements of this study. Only two sets of measurements emerged from the Wilcoxon analysis as indicating significant improvement with the use of one processor over the other. Both the RTI consonant confusion test without lipreading and the Iowa test of medial consonant identification with lipreading indicated better performance with the IP processor at a significance level of $p < 0.05$ (Wilcoxon $T^+ = 20$, $p = 0.03$).

The remaining results presented in Figs. II.A-6 to II.A-8 are those from the MAC battery. Results from the subtests of prosodic perception (timing of syllable boundaries, voice fundamental frequency and word stress) are shown in Fig. II.A-6. These results demonstrate that, in general, these subtests are too easy for the patients and processors under study. The scores for the noise/voice (N/V) and spondee same/different (Sp S/D) tests are very high for all patients and for both processors. The accent test is a more sensitive indicator of performance. Scores for this test show clear differences among patients, but relatively modest differences between processors. Three patients did moderately better with the IP processor on this test, (RC, ET, and MC2) and two patients did moderately better with the CA processor (MC1 and JM). Finally, for the Question/Statement (Q/S) test one patient did much better with the CA processor (MC1), three patients did somewhat better with the IP processor (HE, JM and RC) and two patients obtained identical scores with the two processors (ET and MC2). None of the differences in the means of the results for the two processors is statistically significant among the prosodic subtests of the MAC battery.

Results from the phoneme and word subtests of the MAC battery also demonstrate a general equivalence of the processors for the conditions of our study. These results are presented in Fig. II.A-7. Again, none of the differences in the means of the results for the two processors is statistically significant. Patients HE and MC2 have somewhat higher or equivalent scores on all four tests (including vowel, initial consonant, final consonant, and four-choice spondee) with the IP processor, and patients MC1 and RC have somewhat higher or equivalent scores with the CA processor.

Finally, results from the subtests of open-set recognition are shown in Fig. II.A-8. Once again, none of the differences in the means of the results for the two processors is statistically significant. Patient MC2, however, has higher scores for the IP processor for all four subtests of spondee recognition (Sp), recognition of monosyllabic words (NU6), recognition of CID sentences (CID), and recognition of words in context

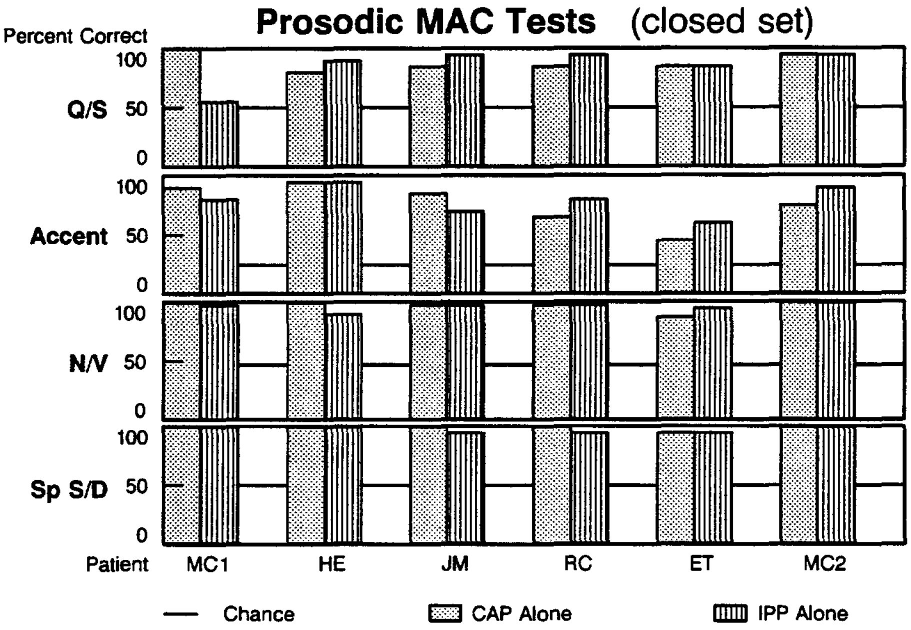


Fig. II.A-6. Results from subtests of the Minimal Auditory Capabilities (MAC) battery designed to evaluate perception of prosodic elements in speech. Abbreviations for the subtests are Q/S for Question/ Statement; N/V for Noise/Voice; and Sp S/D for Spondee Same/Different. The patients are those described in the caption of Fig. II.A-4. All these results are significantly above chance at the $p < 0.01$ level except MC1's score for the Q/S test with the IPP and ET's score for the Accent test with the CAP.

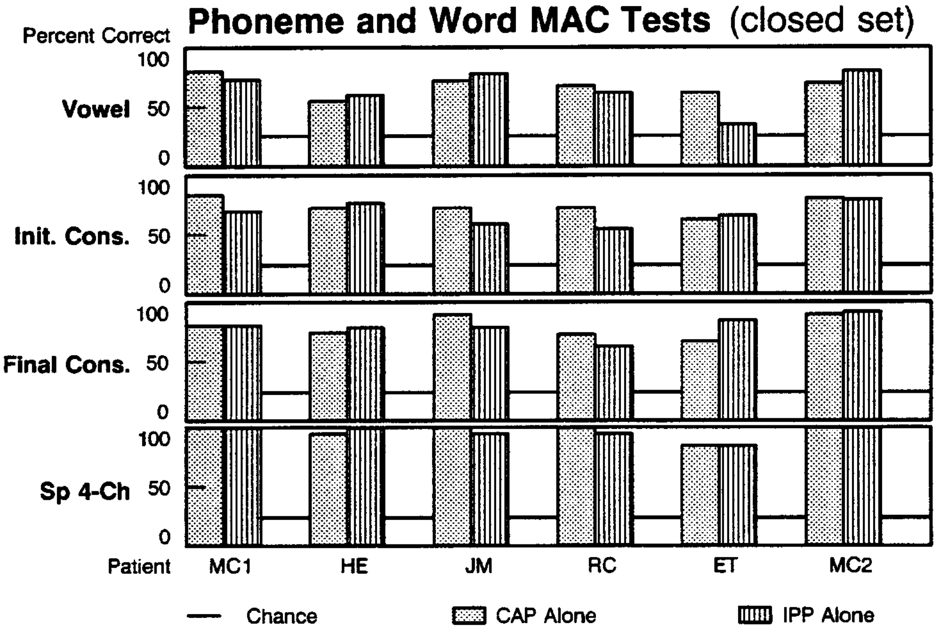


Fig. II.A-7. Results from subtests of the Minimal Auditory Capabilities (MAC) battery designed to evaluate perception of phonemes and words in speech. Abbreviations for the subtests are Init. Cons. for Initial Consonant; Final Cons. for Final Consonant; and Sp 4-Ch for Four-Choice Spondee. The patients are those described in the caption of Fig. II.A-4. All these results are significantly above chance at the $p < 0.01$ level except ET's score for the Vowel test with the IPP.

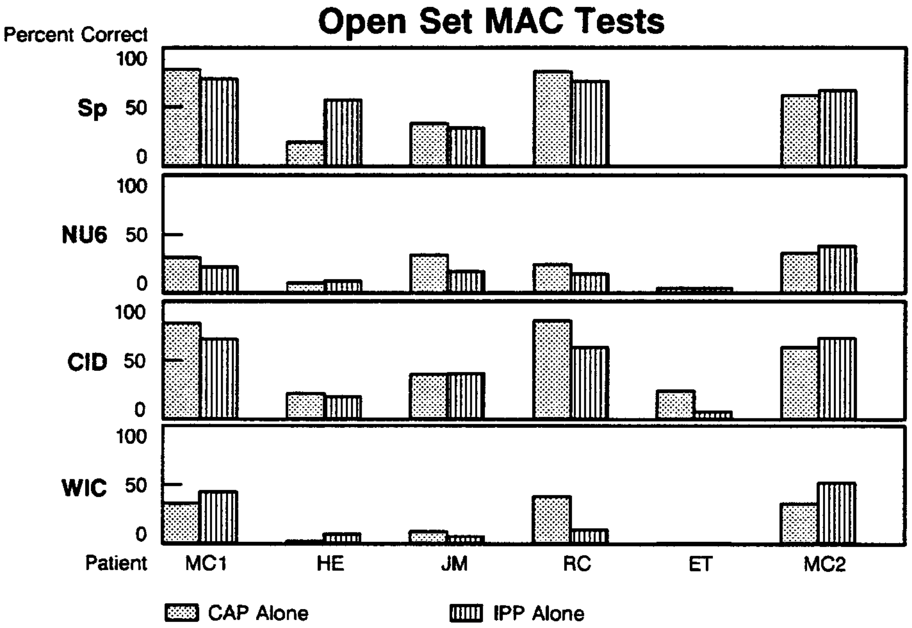


Fig. II.A-8. Results from subtests of the Minimal Auditory Capabilities (MAC) battery designed to measure open-set recognition of speech. Abbreviations for the subtests are Sp for Spondee recognition; NU6 for recognition of monosyllabic words from Northwestern University list six; CID for recognition of everyday sentences from lists prepared at the Central Institute for the Deaf; and WIC for recognition of Words in Context. The patients are those described in the caption of Fig. II.A-4.