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Fifth Quarterly Progress Report

August 1 through October 31, 1993

NIH Contract N01-DC-2-2401

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 represent these parameters for electrical stimulation of the auditory nerve or central auditory structures. Work in the present quarter included the following:

1. Studies with Ineraid subjects SR2, SR10 and SR13, primarily to evaluate effects of parameter changes on the performance of *continuous interleaved sampling* (CIS) processors and to evaluate "virtual channel" CIS (VCIS) processors. Subject SR13 was a new patient in our Ineraid series; subjects SR2 and SR10 returned to the laboratory for follow-up visits.
2. Presentation of project results in invited lectures at the annual meeting of the *American Neurotologic Society* (Minneapolis, MN, October 1, 1993), the annual *Neural Prosthesis Workshop* (Bethesda, MD, October 13-15, 1993), and the *1993 Zhengzhou International Symposium on Electrical Cochlear Hearing and Linguistics* (Zhengzhou, China, October 23-26, 1993). Wilson's participation in the Zhengzhou conference was supported by the Chinese government.
3. Continued preparation of manuscripts for publication.

In this report we present results from the studies to evaluate effects of parameter changes on the performance of CIS processors. In addition, we describe transfer and dissemination of CIS processor technology to commercial manufacturers of cochlear prosthesis systems and to other research groups. Results from the evaluations of VCIS processors will be presented in a future report.

II. Transfer and Dissemination of CIS Processor Technology

An important part of our effort is facilitating the introduction of technology developed by this project into devices that can be used by a large number of deaf people. This involves cooperation with manufacturers and with other research groups. Figure 1 summarizes ways in which results from our NIH-sponsored research have been applied.

We have cooperated with companies in providing **direct engineering assistance** to incorporate our processing strategies, or variations of those strategies, in their commercial implant systems. We have provided such assistance to MiniMed Technologies (now Advanced Bionics) in California, to Med El in Austria, and to Smith & Nephew Richards in Tennessee.

In addition, we have entered into a **cooperative study** with Cochlear Corporation and the Duke University Medical Center to evaluate CIS processors in conjunction with the electrode array used with the present Nucleus 22 implant system. The six subjects of this study will have percutaneous connectors, so that we will have direct electrical access to the electrode array. This will allow implementation of optimized CIS processors and direct within-subject comparisons of CIS strategies and strategies now used with the Cochlear Corporation (Nucleus) device, such as the Multipeak (MPEAK) and Spectral Maxima Sound Processor (SMSP) strategies (see Wilson, 1993, for descriptions of the various strategies).

Research aspects of this cooperative study will be supported by the present NIH project, while all clinical costs associated with the study will be supported by Cochlear Corporation. The study has been approved by the Food and Drug Administration, and surgery for the first patient is scheduled for late January, 1994.

Pending a positive decision from Smith & Nephew Richards on another cooperative study, we also will be involved in the IDE trial of their new implant system.

Other companies and research institutions have produced **independent applications** of the published results of our NIH research without our direct assistance. These applications are listed in the rightmost box of Figure 1 and include incorporation of CIS or CIS-like strategies in portable speech processors developed by Bionic Systems of Antwerp and by research groups in Geneva, Zürich and London.

These various applications were made possible in part by our policy at Research Triangle Institute to donate all results from our NIH-sponsored research on cochlear implants to the public domain. This policy allows simultaneous cooperation with a variety of companies, and helps promote rapid dissemination of research results into commercially available devices.

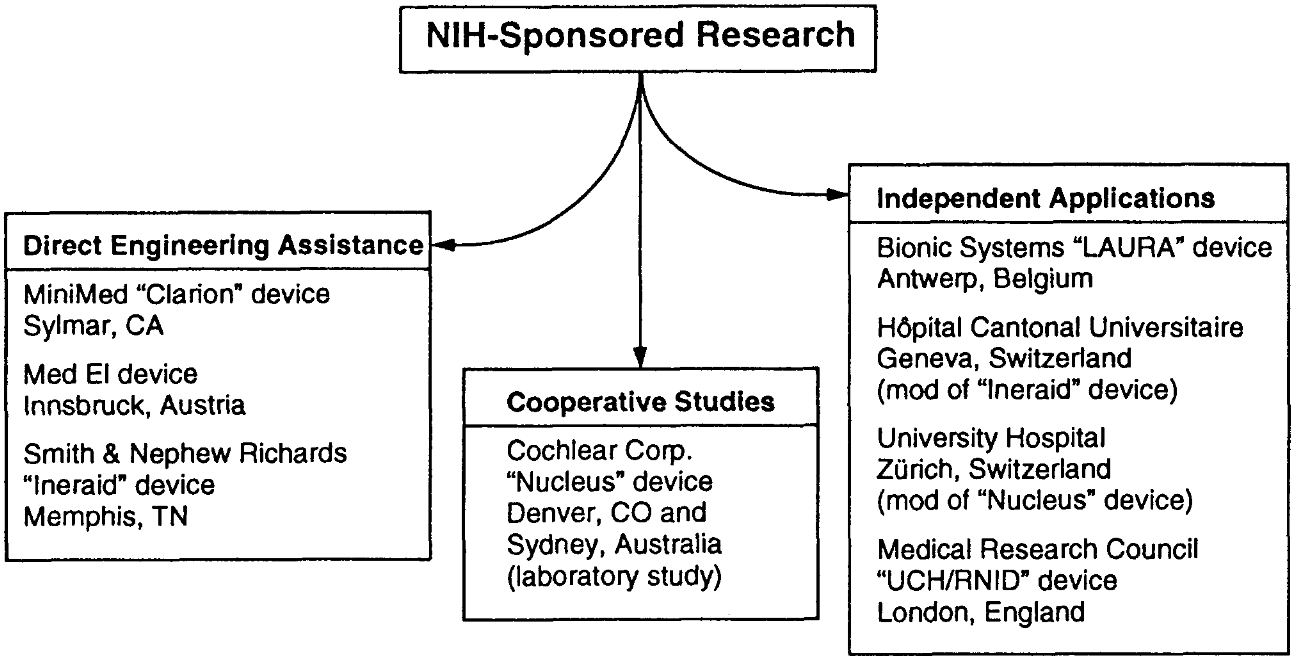

Figure 1. Transfer and dissemination of technology developed under this project.

III. Parametric and Control Studies with CIS Processors

Recent parametric and control studies with CIS processors have included evaluation of effects produced by (a) nonsimultaneous *versus* simultaneous stimulation across channels, (b) changes in pulse duration and pulse rate, and (c) changes in the update order used for each frame of nonsimultaneous stimulation across channels.

Waveforms for a CIS processor are illustrated in Figure 2. The top panels show preemphasized speech inputs (raw speech attenuated at 6 dB/octave below 1200 Hz), with a voiced speech input on the left and an unvoiced speech input on the right. Stimulus waveforms produced by a simplified implementation of a four-channel CIS processor are shown in the middle panels. Pulses are presented in a nonoverlapping sequence across channels, with the pulse amplitudes derived from envelope variations in four contiguous frequency bands of speech. The output of the bandpass filter (and associated envelope detector) with the highest center frequency controls pulse amplitudes for the basalmost electrode (channel 4), and the output of the bandpass filter with the lowest center frequency controls pulse amplitudes for the apicalmost electrode (channel 1).

The temporal sequence of stimulation across electrodes is illustrated in the bottom panel, which is an expanded view of waveforms for the interval indicated by the bracket at the bottom of panel *b*. The update order in this particular implementation of a CIS processor is from base to apex, i.e., electrode 4 is stimulated first, electrode 3 next, electrode 2 next, and electrode 1 last. These 4-3-2-1 frames are repeated continuously for both voiced and unvoiced speech sounds. The duration of each phase of the pulses used for all channels is indicated by the symbol "d" in the trace for channel 2. The interval between sequential pulses on a single channel is indicated by the symbol "1/rate" in the trace for channel 3.

Nonsimultaneous *versus* simultaneous stimulation

The use of nonsimultaneous stimuli is an important feature of CIS processors. Such stimuli eliminate the frank summation of current fields from different electrodes that can occur with overlapping or fully simultaneous stimuli, as in the *compressed analog* (CA) processors of the clinical Ineraid, UCSF/Storz, and MiniMed (when the CA mode is selected) devices (see Wilson, 1993; Wilson et al., 1991).

In a control study we compared standard CIS processors, using nonsimultaneous stimuli, with otherwise identical processors that presented pulses for all channels simultaneously (a time delay was introduced after the simultaneous delivery of pulses to maintain the same pulse rate in each channel for processors using simultaneous or nonsimultaneous stimulation). We expected that speech reception scores might be reduced in the simultaneous-pulses case, inasmuch as increased interactions among channels might degrade the salience of channel-related cues.

The results of such comparisons for three subjects are presented in Figure 3. The processors for each of the subjects were evaluated with tests of consonant identification. Multiple exemplars of each of 16 or 24 consonants were presented in an /a/-consonant-/a/ context from laser videodisc recordings of a male speaker (Tyler et al., 1987). A single block of trials consisted of five randomized presentations of

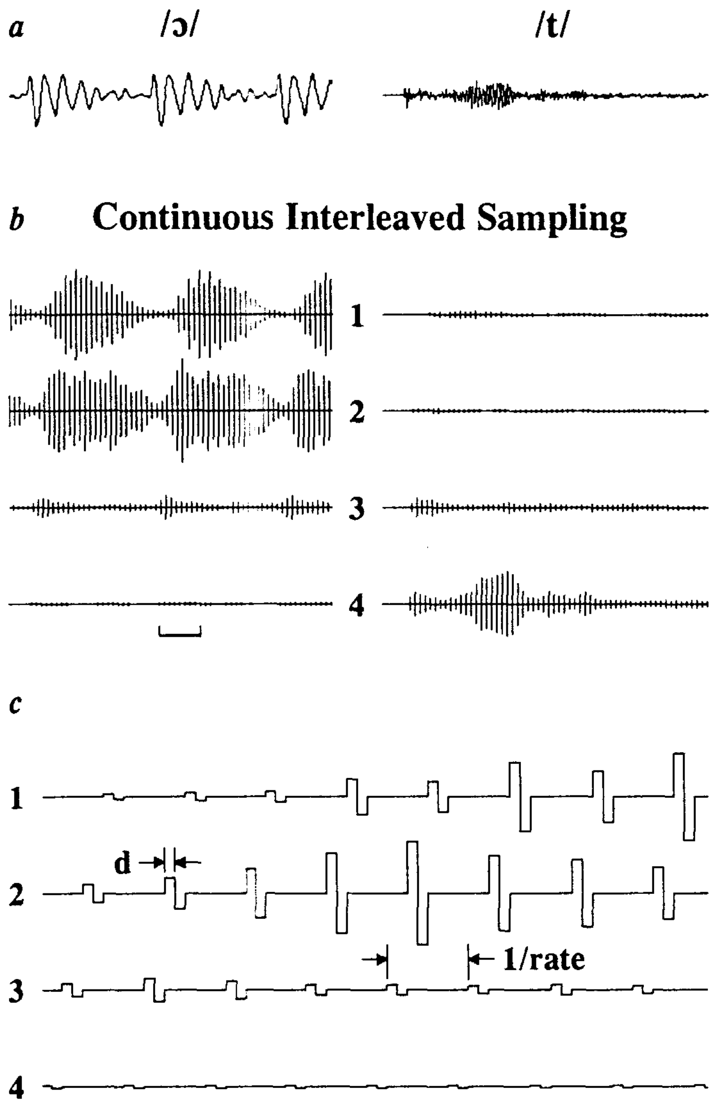

Figure 2. Waveforms of a four-channel CIS processor. *a*, Preemphasized (6 dB/octave attenuation below 1.2 kHz) speech inputs. Inputs corresponding to a voiced speech sound ('aw') and an unvoiced speech sound ('t') are shown in the left and right columns, respectively. *b*, Stimulus waveforms. The waveforms are numbered by channel, with channel 1 delivering its output to the apicalmost electrode. The pulse amplitudes in the illustration reflect the envelope of the bandpass output for each channel. In actual implementations the range of pulse amplitudes is compressed using a logarithmic or power-law transformation of the envelope signal. *c*, Expanded display of CIS waveforms (from the bracketed interval in *b*). Pulse duration per phase ('d') and the period between pulses on each channel ('1/rate') are indicated. The sequence of stimulated channels is 4-3-2-1. [The duration of each trace is 25.4 ms in *a* and *b*, and 3.3 ms in *c*.]

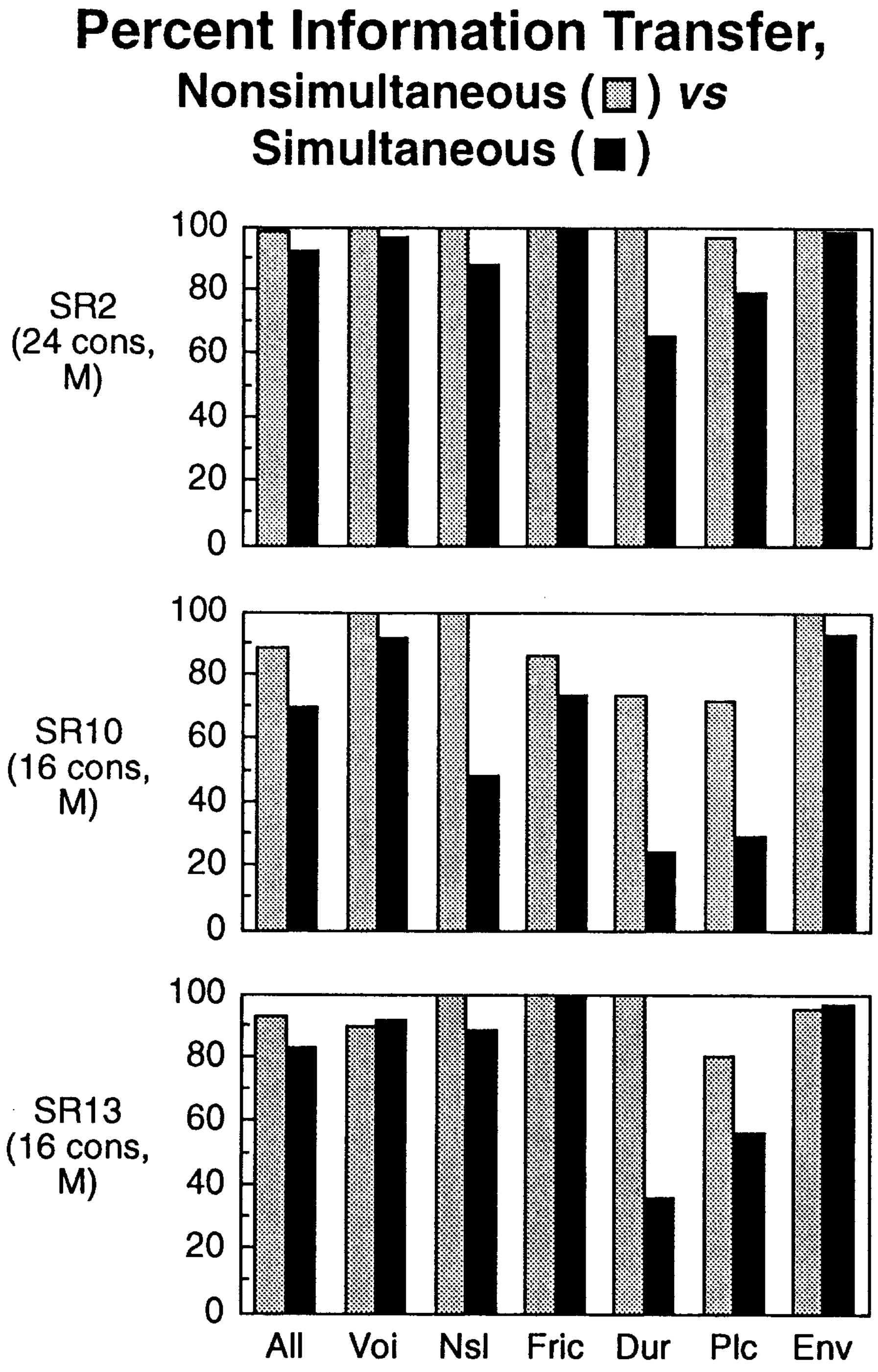

Figure 3. Percent information transfer scores for nonsimultaneous *versus* simultaneous stimulation.

each consonant. At least two blocks were included for each processor tested with each of the subjects. The tests were conducted with hearing alone and without feedback as to correct or incorrect responses.

The results are presented as feature transmission scores, derived from aggregated matrices of stimuli and responses in the consonant tests, according to the method first described by Miller and Nicely (1955). The features include consonant voicing (Voi), nasality (Nsl), frication (Fric), duration (Dur), place of articulation (Plc), envelope cues (Env), and overall information transmission (All). Use of simultaneous stimulation produced a decrement in overall information transmission for all three subjects. In addition, large decrements were observed across subjects for place of articulation and for duration. Subject SR10 also demonstrated a large decrement for nasality. Scores for voicing and envelope cues were similar for the nonsimultaneous and simultaneous conditions. The magnitude of decrements for subject SR2 and SR13 may not have been fully measured, inasmuch as their scores approached or hit the ceiling for most (SR13) or all (SR2) features with nonsimultaneous stimulation.

These results are generally consistent with the idea that simultaneous stimulation degrades the representation of channel-related cues. In particular, scores for place of articulation are substantially reduced when simultaneous stimulation is used instead of nonsimultaneous stimulation. In contrast, the temporal features of voicing and envelope cues appear to be unaffected by the change from nonsimultaneous to simultaneous stimulation. Finally, long duration sounds (the sibilants) may not be well represented with simultaneous stimulation, in that large decreases in transmission scores for the duration feature are seen with the use of simultaneous pulses.

One might expect that the greatest benefits of nonsimultaneous stimulation would be enjoyed by patients with relatively high levels of channel interaction. One of the three subjects in this study required relatively high stimulus levels to reach threshold. Increased current spread at such high stimulus levels, perhaps coupled with relatively poor nerve survival, could lead to high levels of channel interactions.

The left panel of Figure 4 shows all three subjects' thresholds to 50 ms bursts of 33 μs/phase pulses, presented at the rate of 833 pps. The bars show standard errors of the mean for measures across all six electrodes for subjects SR2 and SR10, and across the five apical electrodes for subject SR13 (stimulation of basalmost electrode 6 produced a nonauditory percept for this subject and therefore was not used). The mean threshold for subject SR10 is approximately three times greater than those for subjects SR2 and SR10.

The right panel of Figure 4 shows the percent improvement in the scores for overall information transmission (All) and for place of articulation (Plc) when nonsimultaneous stimulation is used instead of simultaneous stimulation. The results for SR10 demonstrate the greatest relative advantage for nonsimultaneous stimulation, especially for place of articulation, which is represented primarily by channel-related cues. The percent improvement for overall information transmission is less than the improvement for place of articulation for all three subjects, because overall information transmission includes contributions from features not affected by the change from simultaneous to nonsimultaneous stimulation, such as voicing and envelope cues.

An additional aspect of the results presented in Figure 4 is that the relative improvement in scores for

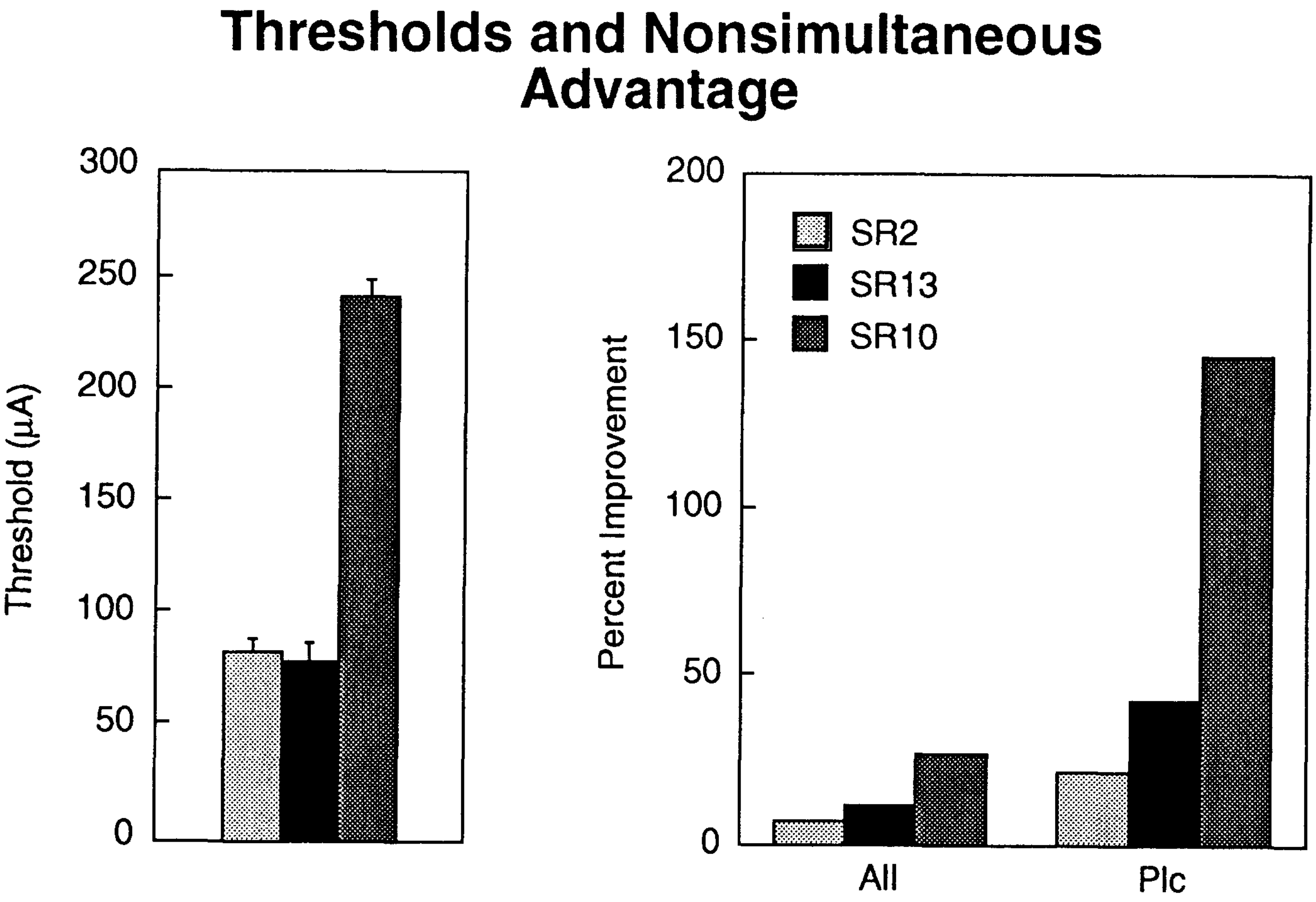

Figure 4. *Left panel*, thresholds to 33 μs/phase pulses presented in a 50 ms burst of pulses at 833 pps. *Right panel*, percent improvement in overall information transfer (All) and feature scores for place of articulation (Plc) when a CIS processor with nonsimultaneous stimulation is used. The error bars in the left panel show the standard error of the mean across electrodes for each of the subjects.

overall information transmission and for place of articulation appear to be greater for subject SR13 than for subject SR2, even though those two subjects have similar (statistically indistinguishable) thresholds. Ceiling effects for the scores of these two features when nonsimultaneous stimulation was used may have reduced the present tests' sensitivity to relative improvements for subject SR2.

Manipulations in pulse duration and pulse rate

In another study we evaluated effects of manipulations in pulse duration and pulse rate on the performance of CIS processors. We report here results for subject SR10. All processors used 6 channels, a staggered order of channel updates (6-3-5-2-4-1), and envelope detectors with a full wave rectifier and a 200 Hz, fourth order (Butterworth) lowpass filter. The relatively low cutoff frequency for the lowpass filter was selected to avoid aliasing at the lowest rate included in this study, 417 pps.

The results are presented in Figures 5 and 6. Figure 5 shows overall information transmission scores from tests of consonant identification (using 16 consonants) with recorded male and female speakers. At least 10 presentations of each consonant (2 blocks) were included for each tested condition in the rate/duration matrices for the male and female speakers. The combined matrices included at least 20 presentations of each consonant, across the two speakers.

Figure 5 shows that, for the male speaker, relatively high scores are obtained for the following conditions: 33 μs/phase pulses presented at the rates of 833, 500 and 417 pps; 67 μs/phase pulses presented at the rates of 833 and 500 pps; and 100 μs/phase pulses presented at the rate of 500 pps. An increase in pulse rate to 2525 pps for 33 μs/phase pulses produces a decrement in overall information transmission for this subject. Decrements also are produced when pulse duration is increased beyond 67 μs/phase for the pulse rate of 833 pps, or beyond 100 μs/phase for the pulse rate of 500 pps, or beyond 33 μs/phase for the pulse rate of 417 pps.

Results for the female speaker are similar in that relatively high scores are again obtained for the conditions of 33 and 67 μs/phase pulses presented at the rate of 833 pps, and of 100 μs/phase pulses presented at 500 pps. A decrement in performance is produced for the female speaker, however, when the rate is either decreased from 833 to 500 pps, or increased from 833 to 2525 pps, for 33 μs/phase pulses.

The results for the combined speakers show a region of high performance for stimulation with 33 or 67 μs/phase pulses at the rate of 833 pps.

Figure 6 shows information transmission scores for the place of articulation feature, for the same tests and conditions of Figure 5. Among features, reception of place information was most affected by changes in pulse duration and pulse rate. Place of articulation also may be the single most important feature for speech recognition using hearing alone (see Dorman et al., 1990; Tyler, 1990; Wilson, 1993).

Regions of high scores for place of articulation are more constrained than the regions for overall information transmission. High place scores are obtained for the male speaker with 33 or 67 μs/phase pulses presented at 833 pps, or with 33 μs/phase pulses presented at 500 pps. One especially high score is obtained for the female speaker with 33 μs/phase pulses presented at 833 pps. Results for the combined male and female speakers show a clear maximum at 33 μs/phase pulses presented at 833 pps.

In all, the best results are obtained with short-duration pulses (e.g., 33 μs/phase), presented at rates of 833 pps or somewhat lower. Such results may reflect tradeoffs among factors, including fine representation of band envelope signals with relatively high rates of stimulation *versus* reductions in temporal channel interactions with greater separation in time between sequential pulses. Busby and colleagues of the Melbourne team have recently suggested that a pulse rate approximately 4 times the highest frequency in the modulation (or envelope) signal might be required for a good representation.

Percent Overall IT, Subject SR10 (4/93)

male

Rate (pps) \ Duration (μs/phase)	33	67	100	167
2525	73			
1365				
833	78	80	74	
500	81	79	79	71
417	78	66		

female

Rate (pps) \ Duration (μs/phase)	33	67	100	167
2525	60			
1365				
833	72	70		
500	64		70	
417				

combined

Rate (pps) \ Duration (μs/phase)	33	67	100	167
2525	62			
1365				
833	72	72		
500	67		69	
417				

Figure 5. Overall information transfer scores (in percent) for CIS processors using different pulse durations and pulse rates. Scores from consonant tests with the male speaker are presented in the left panel, and scores from tests with the female speaker are presented in the middle panel. Scores from combined consonant identification results for the two speakers are presented in the right panel. All processors used 6 channels, a staggered order of channel updates, and envelope detectors with a full wave rectifier and a 200 Hz, fourth order (Butterworth) lowpass filter.

The cutoff frequency of the envelope detectors in the present study was 200 Hz, so rates of around 800 pps or higher might provide good results under that criterion. On the other hand, increased pulse rates, or increased pulse durations at a given rate, might be expected to exacerbate temporal channel interactions. Jay Rubinstein and Don Eddington have suggested that such interactions can be large for pulse separations of less than 150-200 μs (Rubinstein and Eddington, personal communications to Wilson, 1991 and 1993). These two considerations, taken together, suggest that the best speech reception results might be obtained with short-duration pulses presented at a rate near 800 pps. For a 6-channel CIS processor this would provide (a) a pulse rate 4 times higher than the highest frequency in the modulation waveform and (b) approximately 140 μs between sequential 33 μs/phase pulses on different channels.

The tradeoff outlined above may be complicated by still other tradeoffs. For example, increases in pulse rate can produce substantial increases in dynamic range. Such increases in dynamic range could offset negative aspects of high-rate stimulation, e.g., possible increases in temporal channel interactions.

Another possible advantage of high rates is that they may allow the use of higher cutoff frequencies in

Percent Place IT, Subject SR10 (4/93)

Rate (pps)	male				female				combined			
Duration (μs/phase)	33	67	100	167	33	67	100	167	33	67	100	167
2525	39				30				33			
1365												
833	53	53	43		49	34			49	41		
500	57	50	50	36	33		34		41		39	
417	49	28										

Figure 6. Percent information transfer for the place of articulation feature, for the same tests and conditions presented in Figure 5.

the envelope detectors while still providing a good representation of the envelope signal. This advantage, if present, also could offset negative aspects of high-rate stimulation.

It seems likely that these various factors might interact in different ways and to different degrees in different patients. Patients with low levels of temporal channel interactions, for instance, may obtain their best results at relatively high rates of stimulation, where they can enjoy the benefits of such stimulation without suffering the downside of substantially increased channel interactions. We plan studies with additional subjects to evaluate the possibility of different tradeoffs across subjects and, concomitantly, to evaluate the generality of the results obtained with subject SR10.

Staggered *versus* apex-to-base stimulation

In most implementations of CIS processors to date, we have used a "staggered" order of channel updates to impose the maximum possible spatial separation between sequentially stimulated channels, across each stimulus frame (e.g., for a 6-channel processor an order of 6-3-5-2-4-1 is used). This order was designed to reduce temporal channel interactions.

In prior studies we have compared the staggered order with a base-to-apex order in speech reception tests with several subjects. A base-to-apex order of stimulation mimics the direction of the traveling wave of mechanical displacements along the basilar membrane found in normal hearing. We therefore anticipated a possible advantage to the base-to-apex order. The results, however, showed that the staggered order was as good as, or substantially better than, the base-to-apex order for the studied subjects. A release from temporal channel interactions may have contributed to the instances of improvement.

As a control, we also have begun comparisons with CIS processors using staggered *versus* apex-to-base stimulation. We expected that the apex-to-base order might produce a decrement in performance, inasmuch it (a) would most likely have the same effect on channel interactions as base-to-apex stimulation and (b) was opposite to the direction of the traveling wave found in normal hearing.

Results for two subjects are presented in Figure 7. As in other studies, the processors were evaluated with tests of consonant identification. Ten presentations of each of 16 consonants by the male speaker, and ten presentations of each of the consonants by the female speaker, were included in the tests with subject SR10 for each processor. For SR13, ten presentations of each of the consonants by male speaker were included in the tests with each processor.

To our surprise, the apex-to-base order was clearly superior for both subjects. Large increases in information transmission for place of articulation are seen for both subjects when the apex-to-base order is used. In addition, this order produces large gains in the transmission of voicing, duration, and envelope information for subject SR13. The scores for the voicing and envelope features for subject SR10 approach or hit the upper scale limit for both processors. Improvements in these categories for him therefore may have been masked by possible ceiling effects.

Both subjects expressed a strong preference for the apex-to-base order. Each said that processors using this order sounded more natural, more intelligible, and lower in overall pitch than otherwise identical processors using the staggered update order.

Studies with additional subjects are needed to evaluate the generality of the present results. For now, we can say that improvements may be produced for at least some subjects using an apex-to-base stimulation order.

Review of processor improvements for subject SR10

Findings presented in the previous sections indicate that choices of pulse rate, pulse duration, and channel update order can have large effects on the performance of CIS processors. Such effects are further illustrated in Figure 8, which shows a history of improvements for subject SR10, over the course of repeated visits to our laboratory.

Included in the figure are results from the consonant test, with male and female speakers, and from two tests of open set speech recognition. The open set tests measured recognition of 100 key words in the Central Institute for the Deaf (CID) sentences of everyday speech and of 50 monosyllabic words from Northwestern University Auditory Test 6 (NU-6). The error bars show standard errors of the mean for the consonant test. At least 10 repetitions of each of 16 consonants were used for each speaker and each processor condition. All tests were conducted with hearing alone, using recorded material, and without feedback as to correct or incorrect responses.

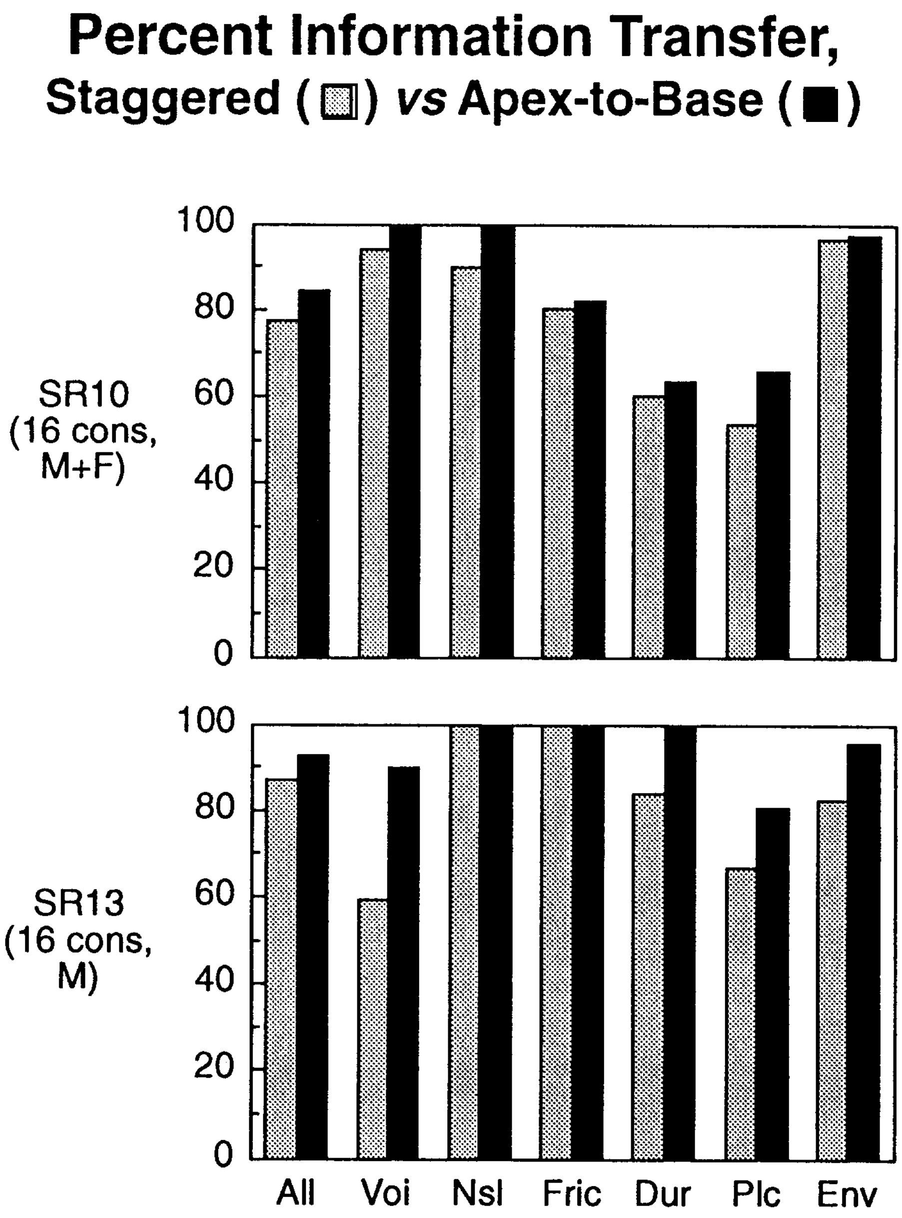

Figure 7. Percent information transfer scores for staggered *versus* apex-to-base stimulation.

In the first visit, SR10 was fitted with a CIS processor using relatively long pulses (167 μs/phase), a relatively low pulse rate (500 pps), and a staggered order of channel updates. As shown in the figure, application of this processor produced a quite large improvement over the clinical CA processor used by SR10 in his daily life. The score for consonant identification improved from 25 to 56 percent

Processor Improvements, SR10

	Proc	Ch	Dur	Rate	Order	Date
░	CA	4				11/91
■	CIS	6	167	500	stag	11/91
▒	CIS	6	33	833	stag	4/93
▓	CIS	6	33	833	a-b	10/93

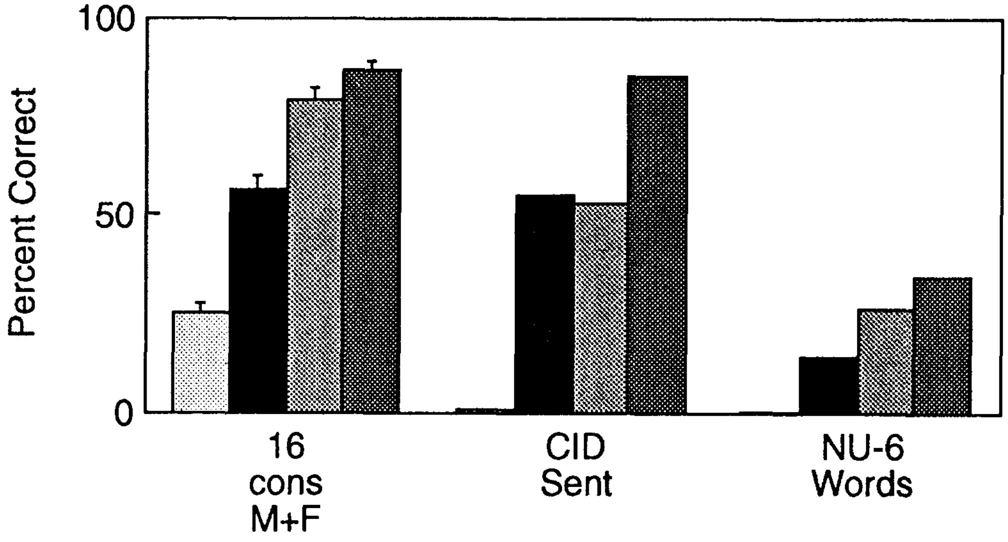

Figure 8. Improvements in speech processor performance for Ineraid subject SR10. The table above the bar chart specifies different processors. The leftmost column indicates the general strategy, *compressed analog* (CA) or *continuous interleaved sampling* (CIS). The remaining columns indicate, from left to right, the number of channels (Ch) in CA or CIS processors, the duration per phase (Dur) of pulses used in CIS processors, the rate of pulses on a single channel in CIS processors (Rate), the order of channel updates used in CIS processors (Order; the order is either staggered [stag] or apex-to-base [a-b]), and the date of testing. The error bars show standard errors of the mean for the consonant test.

correct. The scores for the open set tests also improved, from 1 to 55 percent correct for the CID test and from 0 to 14 percent correct for the NU-6 test. These increases in performance were obtained with no more than several hours of aggregated experience with CIS processors, compared with more than a year of daily experience with the clinical CA processor.

Following this visit, SR10 returned to his home and resumed use of the clinical CA processor.

We later asked SR10 to return to the laboratory for a second visit, this time to evaluate effects of manipulations in pulse duration and pulse rate. As described in a prior section of this report, the best combination of tested durations and rates for SR10 was 33 μs/phase pulses presented at 833 pps. We decided at the end of the visit to evaluate fully a CIS processor using these parameters. We also repeated the consonant test for the clinical CA processor, to evaluate the possibilities that SR10's performance with that processor had improved through additional daily experience, or that SR10's performance on the consonant test had improved through additional practice and familiarity with the test.

SR10 again obtained a score of 25 percent correct for the consonant test (male and female speakers) with the CA processor. Scores for the CIS processor were generally better than those obtained during the first visit, with a CIS processor using a much longer pulse duration and a lower pulse rate. The score for the consonant test improved from 56 to 79 percent correct; the score for the CID stayed about the same, from 55 to 53 percent correct; and the score for the NU-6 test almost doubled, from 14 to 26 percent correct.

Following this visit, SR10 again returned to his home and resumed use of the clinical CA processor.

We asked SR10 to return to the laboratory for a third visit, this time to conduct a variety of tests with CIS and "virtual channel" CIS processors. One of the tests with CIS processors was to compare different channel update orders, as described in the previous section of this report, wherein an apex-to-base order produced an improvement over the staggered order. Based on this finding, we again decided at the end of the visit to evaluate a CIS processor with an apex-to-base update order in greater detail, and to repeat the consonant test for the clinical CA processor.

SR10's performance on the consonant test with the CA processor improved, from 25 to 37 percent correct. Most of the improvement was for the female speaker. The improvement may have reflected better use of cues provided by the CA processor through additional experience, or increased familiarity with the consonant test, or both.

Performance with the apex-to-base CIS processor was substantially better than performance with an otherwise identical processor using a staggered update order. The score for the consonant test improved from 79 to 87 percent correct; the score for the CID test from 53 to 85 percent correct; and the score for the NU-6 test from 26 to 34 percent correct.

This pattern of sustained improvements across visits is remarkable. SR10 went from zero or near zero levels of open set recognition with the clinical CA processor to high levels with the final CIS processor. Indeed, as recently as several years ago the scores of 85 percent correct for the CID test and 36 percent correct for the NU-6 test would have been regarded as "star" levels of performance for a cochlear implant patient. The present results show what is possible for at least some patients at the low end of the clinical performance spectrum. These results also demonstrate dramatically the importance of parameter choices for CIS processors.

IV. Summary

Major conclusions presented in this report include the following:

1. CIS is becoming available for widespread clinical use.
2. CIS performance may be improved through good choices of pulse width, pulse rate, and channel update order. Large gains may be realized with good choices, as illustrated by our case with subject SR10, who went from zero or nearly zero levels of open set performance with his clinical CA processor to high levels of open set performance with CIS processors. Both consonant identification and open set performance were improved with appropriate manipulations in pulse width, pulse rate, and channel update order.
3. Nonsimultaneous stimulation is important, perhaps especially so for patients with relatively high thresholds to pulses.

V. Plans for the Next Quarter

In the next quarter we plan extensive studies with two patients using a forward masking technique (Lim et al., 1989), to measure the spatial patterns of neural excitation produced with stimulation of single electrodes in the Ineraid implant, and with coordinated stimulation of multiple electrodes, as used in VCIS and "sharpened field" CIS processors. The results should allow us to estimate the degree of control over the excitation field afforded by these various stimuli. It may be that only gross control can be achieved with monopolar electrodes. Alternatively, the results may suggest possibilities for improved control, especially with sharpened field stimuli.

The forward masking studies will be paired with psychophysical studies of stimulus identification and stimulus scaling, where the stimuli will include those used in CIS and VCIS processors. In one experiment, for example, we will include single-electrode and dual-electrode stimuli, as in the VCIS processors described in QPR 1 for this project. Anecdotally such stimuli elicit equal increases in perceived pitch from apex to base, i.e., the lowest pitch is produced by stimulation of electrode 1 alone, the next highest pitch by stimulation of electrodes 1 and 2 together, the next highest pitch by stimulation of electrode 2 alone, and so on. Formal scaling experiments should allow us to evaluate the anecdotal reports. Equal increments in pitch should be demonstrated as significantly different and roughly equal increments in pitch scaling judgments across the stimuli. Formal identification experiments should allow us to measure the perceptual independence among the stimuli. If certain pairs of stimuli are not independent, then elimination of one member of the pair might produce an improvement in a speech processor design.

In addition to the forward masking and psychophysical studies outlined above, our plans for the next quarter include the following:

1. We will attempt measures of intracochlear evoked potentials, using pairs of unstimulated electrodes in the Ineraid implant. A recording system has been designed with a fast-recovery amplifier and with optional blanking of the amplifier input during delivery of short-duration pulses. These features may allow the recording system to regain full sensitivity within 10s of milliseconds after a pulse is delivered. If so, we should be able to record compound action potentials in response to trains of pulses, presented at various pulse rates, and to sinusoidally amplitude modulated (SAM) pulse trains. Such results would be valuable in demonstrating the temporal patterns of population responses to repetitive stimuli. The recording system is under construction and will be evaluated with an Ineraid electrode immersed in saline. The *in vitro* studies may well lead to refinements in the recording system prior to its use in patient studies.
2. Our proposed studies with six patients having percutaneous access to an implanted Nucleus electrode array have been approved by the Food and Drug Administration. The fist patient is scheduled for surgery in late January, 1994. We may assist in the surgery by measuring electrode impedances, and we will continue our preparation for laboratory studies with these patients, to begin in late April or early May of 1994.
3. Presentation of project results in an invited faculty lecture at the *5th Annual Audiology Videoconference*, sponsored by the Mayo Foundation and the Sheldon Reese Foundation. Fifty host sites will participate in the conference (November 6).

4. Continued preparation of manuscripts for publication, including an invited paper for the *American Journal of Otology*, "New processing strategies in cochlear implantation."

VI. Acknowledgments

We thank the three subjects of the studies described in this report for their enthusiastic participation and generous contributions of time. We also are grateful to M.F. Dorman, D.K. Eddington, C.C. Finley and R.V. Shannon, who helped us with various scientific aspects of the work.

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Appendix 1

Summary of Reporting Activity for the Period of

August 1 through October 31, 1993

NIH Project N01-DC-2-2401

Reporting activity for the last quarter included publication of one paper and presentations of five invited lectures. Citations are listed below.

Paper

Wilson BS, Finley CC, Lawson DT, Wolford RD, Zerbi M: Design and evaluation of a continuous interleaved sampling (CIS) processing strategy for multichannel cochlear implants. *Journal of Rehabilitation Research and Development* 30: 110-116, 1993.

Presentations

Wilson BS: New processing strategies in cochlear implantation. *Annual Meeting of the American Neurotologic Society*, Minneapolis, MN, October 1, 1993.

Wilson BS: Speech processors for auditory prostheses. *Neural Prosthesis Workshop*, Bethesda, MD, October 13-15, 1993.

Wilson BS: Introduction to speech processor design and speech testing. *1993 Zhengzhou International Symposium on Electrical Cochlear Hearing and Linguistics*, Zhengzhou, China, October 23-26, 1993.

Wilson BS: New processing strategies for cochlear prostheses. *1993 Zhengzhou International Symposium on Electrical Cochlear Hearing and Linguistics*, Zhengzhou, China, October 23-26, 1993.

Wilson BS: Further studies with CIS and related processors. *1993 Zhengzhou International Symposium on Electrical Cochlear Hearing and Linguistics*, Zhengzhou, China, October 23-26, 1993.

Sixth Quarterly Progress Report

November 1, 1993 through January 31, 1994

NIH Contract N01-DC-2-2401

Speech Processors for Auditory Prostheses

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CONTENTS

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 represent those parameters for electrical stimulation of the auditory nerve or central auditory structures. Work in the present quarter included the following:

1. Studies with Ineraid subjects SR2 and SR10. The studies for both subjects included (a) successful recording of intracochlear evoked potentials in response to trains of pulses, with a variety of pulse rates and pulse amplitudes, and to sinusoidally amplitude modulated (SAM) pulse trains, and (b) use of a forward masking technique to assess the spatial patterns of neural excitation produced by stimulation of single electrodes in the Ineraid implant and by coordinated stimulation of multiple electrodes.
2. Preliminary evaluation of an implant system proposed for use in China, in tests with subject SR10. The system includes a four-channel CIS processor and a four-channel transcutaneous transmission system, using four separate pairs of transmitting and receiving coils. In the studies with SR10 the outputs of the four passive receiving coils were routed to the implanted electrodes via the percutaneous connector of the Ineraid device.
3. Participation in the surgery and initial processor fitting for the first in a series of six patients to have percutaneous connectors in conjunction with Nucleus electrode arrays. Research studies with this first patient are scheduled to begin in May, 1994.
4. Presentation of project results in invited lectures at the *5th Annual Audiology Videoconference*, sponsored by the Mayo and Sheldon Reese Foundations (Jacksonville, FL, November 6), and at the University of Iowa, Department of Otolaryngology -- Head & Neck Surgery (Iowa City, IA, January 18).
5. Completion of an interface system to allow direct laboratory control of the implanted receiver in the MiniMed device. This system will be used in a series of psychophysical and speech reception studies with patients implanted with the Clarion cochlear prosthesis.
6. Continued preparation of manuscripts for publication, including completion of an invited paper for the *American Journal of Otology*, on "New processing strategies in cochlear implantation."

In this report we present results from prior studies with Ineraid subjects SR2, SR10 and SR13 to evaluate "virtual channel" CIS (VCIS) processors. Results from the evoked potential and forward masking studies indicated in point 1 above, and the evaluation of the prosthesis system proposed for use in China (point 2), will be presented in future reports.

II. Evaluation of VCIS Processors

Initial studies with "virtual channel" CIS (VCIS) processors have been described in Quarterly Progress Reports 1 and 3 for this project. The concept of virtual channels was introduced in QPR 1. Results from speech reception tests with one subject also were presented in that report. Results from psychophysical studies of virtual channel stimuli were presented in QPR 3. In the present report we summarize these prior results and present new results from evaluation of VCIS processors with reduced numbers of electrodes and from comparisons of CIS and VCIS processors in tests with additional subjects.

Percepts elicited by VCIS stimuli

Virtual channels involve simultaneous stimulation of two or more electrodes and may be used in VCIS processors to provide pitch percepts that are different from those elicited by stimulation of single electrodes. VCIS processors thereby offer the possibility of increasing the number of effective channels beyond the number of available electrodes.

The construction of various types of virtual channels is illustrated in Fig. 1. The top curve in each panel is a hypothetical sketch of the number of neural responses, as a function of position along the cochlea, for a given condition of stimulation. The condition of stimulation is indicated by the pulse waveform(s) below each dot, with the dots representing the positions of three adjacent electrodes. Conditions involving stimulation of one electrode only are shown in panels *a* and *b*, and conditions involving simultaneous stimulation of more than one electrode are shown in panels *c* through *g*.

As indicated in our previous reports, Ineraid subject SR2 can rank conditions *a* through *f* according to their distinct pitches. Stimulation of apicalmost electrode 1 alone (condition *a*) produces a low pitch, whereas stimulation of electrode 2 alone (condition *b*) produces a higher pitch. Simultaneous stimulation of both electrodes, with identical pulses having approximately half the amplitude of the single-pulse conditions (condition *c*), produces an intermediate pitch. Pairing stimulation of electrode 1 with a reversed-polarity pulse on electrode 2 (condition *d*) produces the lowest pitch among the illustrated conditions. Similarly, pitches higher than that elicited with stimulation of electrode 6 alone (the basalmost electrode in the Ineraid array) can be produced by presenting a reversed-phase pulse (of lower amplitude) on electrode 5. Additional pitches between electrodes can be produced by constructing triads of pulses, as illustrated in panels *e* and *f*. The pitch produced with the stimulus of condition *e* is lower than that elicited with stimulation of electrode 2 alone (condition *b*), whereas the pitch produced with the stimulus of condition *f* is higher than that elicited with stimulation of electrode 2 alone.

Condition *g* in Fig. 1 suggests a way in which the width of a neural excitation field might be reduced without altering the centroid or peak of the field, by supplying reversed-polarity pulses on either side of a principal pulse. Subject SR2 reports that the pitch percept of this condition is indistinguishable from that of condition *b*. We note that this general type of "sharpened field" stimulation also has been described by Townshend and coworkers (1987) and by Jolly, Spelman and Pfingst (1994).

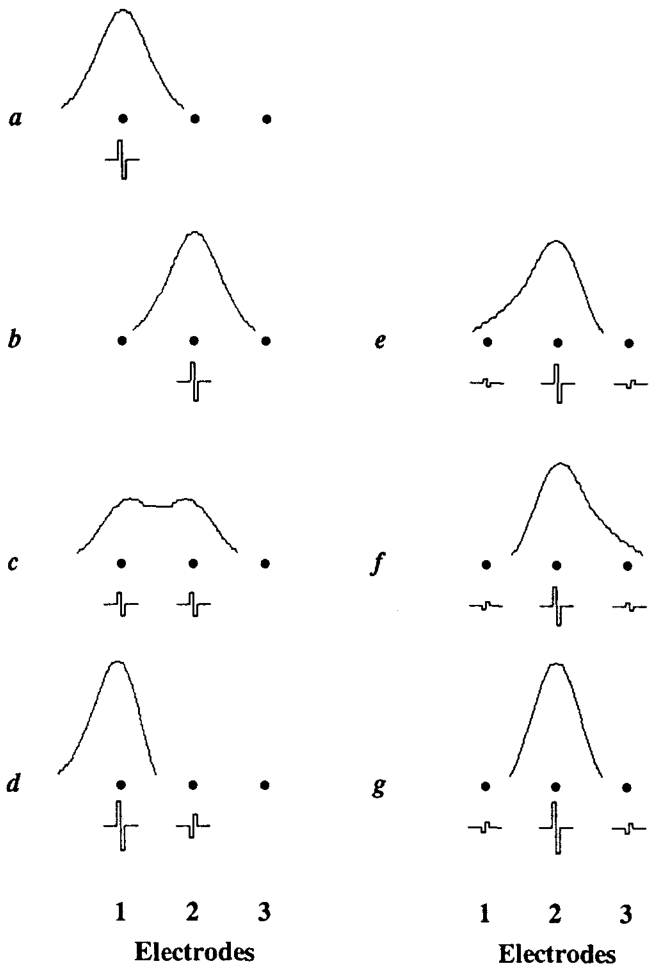


Fig. 1. Conditions of single-electrode and multiple-electrode (virtual channel) stimulation. See text for a description of the different types of information presented in each panel.

Ineraid subjects SR10 and SR13 also have participated in psychophysical studies to evaluate perceptual differences among virtual channel and single-electrode stimuli. Subject SR10 was tested with conditions *a* through *c* and subject SR13 with conditions *a* through *d*. The results were the same as those indicated above for SR2.

Initial CIS/VCIS comparison

One implementation of a VCIS processor is illustrated in Fig. 2. The virtual channels use identical in-phase pulses presented simultaneously on adjacent electrodes. These channels are combined with six single-electrode channels to form an 11 channel processor. As in standard CIS processors, the stimulus for each of the channels is presented in a nonoverlapping sequence. Without such interleaving of

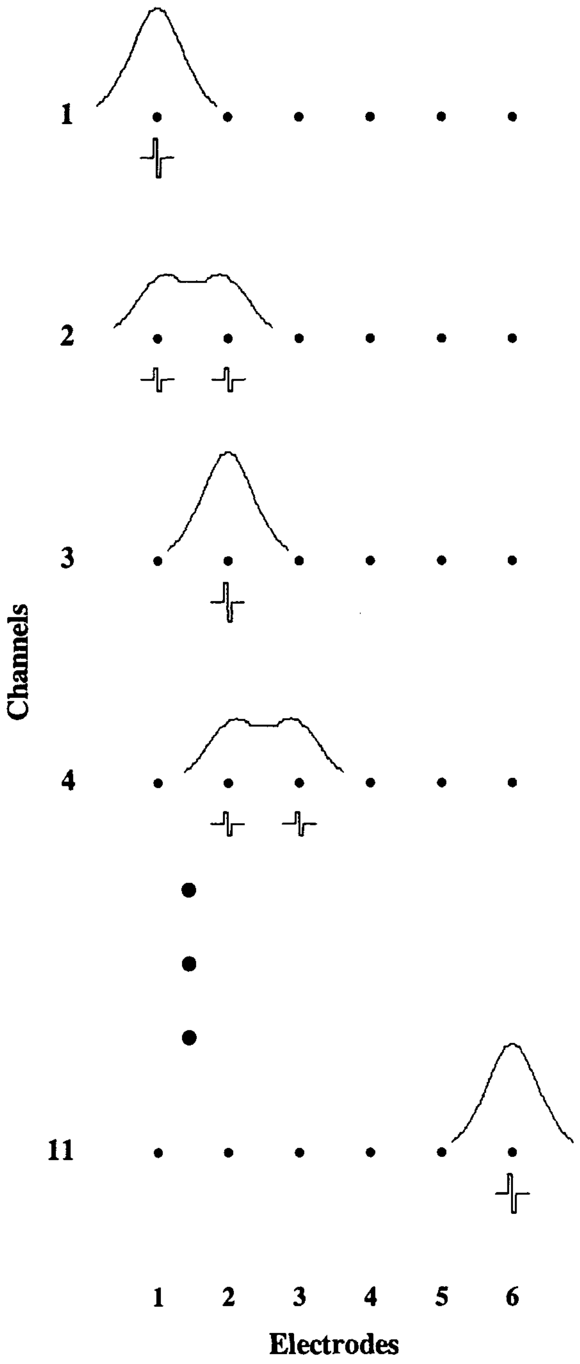


Fig. 2. Construction of an 11 channel VCIS processor.

stimuli, electric fields from other electrodes would interact (i.e., sum) with the fields produced by the stimulus for any given channel, thereby reducing the independence among channels.

An 11 channel VCIS processor of the type illustrated in Fig. 2 has been compared with 6 channel CIS processors in initial tests with subject SR2 (QPR 1; Wilson et al., in press). This subject has participated in an extensive series of studies to evaluate effects of parametric changes in CIS processors and more recently to evaluate implementations of VCIS processors. Results from his first tests with CIS processors are presented in earlier reports from our group (e.g., Wilson et al., 1991) and are summarized here in Table 1 for reference. The tests included open-set recognition of 25 two-syllable words (spondees), 100 key words in the Central Institute for the Deaf (CID) sentences of everyday speech, the final word in each of 50 "high predictability" sentences in the Speech Perception in Noise (SPIN) test (presented without noise in our studies), and 50 one-syllable words from Northwestern University Auditory Test 6 (NU-6). All tests were conducted with hearing alone and the test items were presented from standard recordings without feedback or repetition.

These tests and others have been used to evaluate the subsequent implementations of CIS and VCIS processors. Results from a refined implementation of a CIS processor, using parameters somewhat different from those of the original implementation, are presented in the second column of numeric entries in Table 1. Results for the 11 channel VCIS processor are presented in column 3. As a precaution against possible learning or familiarization effects, different lists of words and sentences were used in each of the CID, SPIN and NU-6 tests for the different processors. Also, the NU-6 test was repeated for the "refined CIS" processor using another new list of words. The additional test listed in Table 1 involved identification of 24 consonants in an /a/-consonant-/a/ context. Each of the 24 was presented in block-randomized order 10 times for a male speaker and 10 times for a female speaker. As with the other tests, the medial consonant tokens were presented in a sound-alone condition, with no feedback as to correct or incorrect responses.

Scores for all three processors are quite high. Indeed, most of the scores are at or near the upper scale limits for each of the tests. The only exception is the NU-6 test, for the two implementations of CIS processors. The NU-6 scores indicate an improvement in performance with the refined CIS processor over the original implementation. The refined processor used a somewhat higher rate of stimulation on each channel (2500 *versus* 1515 pps), shorter pulses (33 *versus* 55 μs/phase), a higher corner frequency for the input equalization filter (1200 *versus* 600 Hz), sharper bandpass filters (12th *versus* 6th order), and a lower cutoff frequency for the lowpass filters in the envelope detectors (400 *versus* 800 Hz). Also, the refined processor was evaluated in the 10th week of testing various CIS and other processors with this subject, spread over a three-year period. Learning or practice effects associated with this additional experience also may have contributed to his improved scores (Dorman et al., 1990; Dowell et al., 1987; Tyler et al., 1986).

With the 11 channel VCIS processor SR2 achieved a score of 98% correct on the NU-6 test, making only one phoneme error (149/150 phonemes). He obtained scores of 100% correct on all remaining open-set tests, and a score of 97% correct on the consonant test.

Evaluation of VCIS processors with reduced numbers of electrodes

Following the initial comparison of CIS and VCIS processors, we decided to evaluate a variety of CIS and VCIS processors with reduced numbers of electrodes. The principal motivation for these additional

TABLE 1. Percent correct scores from speech tests with 6-electrode processors, subject SR2. The processors included a 6-channel CIS processor, a refined 6-channel CIS processor, and an 11-channel VCIS processor.

Test	CIS	Refined CIS	VCIS[a]
Spondees	96	100	100
CID	100	100	100
SPIN	96	100	100
NU-6	80	90,94[b]	98
Consonants	*	98.1±0.7[c]	97.1±0.8

[a] VCIS and refined CIS processors both used 12th-order bandpass filters, fullwave rectifiers, 400 Hz lowpass filters (1st order), and 33 μs/phase pulses. The rate of stimulation for each channel was 1365 pps for the VCIS processor and 2500 pps for the refined CIS processor.

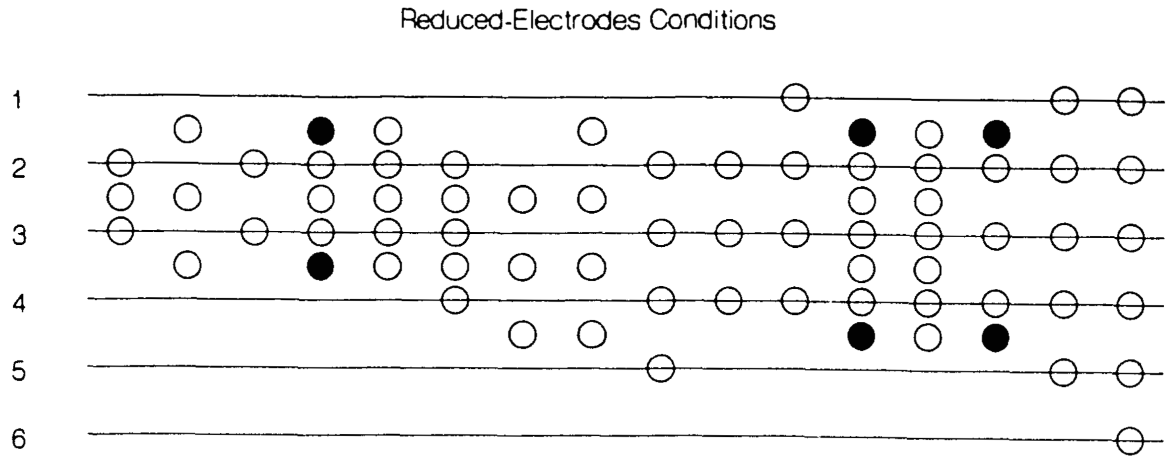
[b] Scores from two separate administrations of the NU-6 test; total phoneme score was 287/300.

[c] SEM of block percent-correct scores.

*The 24 consonant test was not conducted during this initial fitting and evaluation of a CIS processor.

studies was to reduce test scores to a range where differences among processors might be clearly demonstrated. In addition, we were interested in evaluating the potential benefit of virtual channels for patients with a limited number of usable electrodes.

The conditions and results of the additional studies, again with subject SR2, are presented in Fig. 3. The horizontal lines indicate the positions of six physical electrodes. An open circle on one of the lines indicates a channel of stimulation with a single electrode. An open circle between lines indicates a virtual channel formed by stimulation of adjacent electrodes with identical in-phase pulses (corresponding to condition *c* in Fig. 1). A closed circle indicates a virtual channel formed by presentation of a principal pulse at one electrode paired with simultaneous presentation of a reversed-polarity half-amplitude pulse on an adjacent electrode (corresponding to condition *d* in Fig. 1). As an example, the leftmost condition in Fig. 3 is that of a three-channel processor using two single-electrode channels and one virtual channel. Electrodes 2 and 3 are used for the single-electrode channels, and electrodes 2 and 3 are stimulated together with identical in-phase pulses for the virtual channel. The next condition in Fig. 3 also has three channels, but in this case each of the channels is a virtual channel formed with identical in-phase pulses. The next condition uses the three channels of the first condition along with two additional virtual channels formed with reversed-polarity pulses. The apicalmost virtual channel is produced by simultaneous stimulation of electrode 2 with a principal pulse and electrode 3 with a reversed-polarity pulse at half the amplitude of the principal pulse. Similarly, the basalmost virtual channel is produced with a principal pulse on electrode 3 and a reversed-polarity pulse on



Processor	171	181	164	157a	168a	156a	182	191	183	155a	184	158a	167a	170	154a	195
Cons. IT Overall	87	87	89	89	90	91	92	92	92	93	93	94	94	95	98	100
Place	58	64	66	69	70	78	72	77	75	77	79	79	80	86	94	100

Fig. 3. Conditions and results of reduced-electrodes study. See text for explanation of symbols denoting conditions at the top of the figure. Results from tests of consonant identification are presented at the bottom, and include overall information transfer (Cons. IT Overall) and information transfer for the place of articulation feature (Cons. IT Place).

electrode 2. Note that in this condition five channels of information are presented with only two electrodes.

The processors for each of the conditions in Fig. 3 were evaluated with the consonant test. Each of the 24 consonants was presented at least 10 times with the male speaker for each of the conditions. The results are presented in terms of overall information transfer (Cons. IT Overall) and the information transfer score for the place of articulation feature (Cons. IT Place). The results and conditions are arranged in order of increasing scores for overall information transfer.

The ranking of conditions from left to right seems to indicate improvements in scores with increases in the total distance along the cochlea spanned by the channels. The addition of virtual channels *per se* does not appear to improve scores, even with an increase the number of channels. Improvements in scores can be produced by increasing cochlear distance either with single-electrode channels or with virtual channels.

TABLE 2. Independent variables used in the stepwise linear regression analyses of results from the reduced-electrodes study.

Variable	Description
nchans	number of channels
Pivc	fraction interior virtual channels
eacr	exterior virtual channels, reversed phase
eacin	exterior virtual channels, in phase
dist	total cochlear distance swept by the channels
center	center of cochlear distance
space	average spacing between channels
ratio	number of channels / number of electrodes
vc	presence of virtual channels

To evaluate these impressions, we conducted a stepwise linear regression analysis of the data, where the dependent variable was either overall information transfer or information transfer for the place of articulation feature. The independent variables included those listed in Table 2.

The regression analyses indicated that the single variable of cochlear distance accounted for 83.3% of the variance in the overall IT scores ($p < .000002$) and for 84.1% of the variance in the place IT scores ($p < .000002$). No other variable accounted for a significant portion of the variance for either dependent variable. The regression equations were:

$$\text{Overall IT} = 3.1 * \text{dist} + 84.2$$

$$\text{Place IT} = 9.6 * \text{dist} + 51.8$$

The addition of interior virtual channels does not figure in the regression analyses. It may be that much of the information on intermediate pitches already is available with CIS processors, using single-electrode channels. That is, even though stimuli are presented nonsimultaneously, intermediate pitches might be produced between adjacent electrodes. A critical question relates to the time over which the central auditory system integrates inputs to make inferences about pitch. Recent studies by Colette McKay and Hugh McDermott of the Melbourne team (personal communication to Wilson, 1993) suggest that this interval is at least 400 μs, which is much longer than the time between sequential pulses in typical implementations of CIS processors.

CIS/VCIS comparisons with additional subjects

In parallel with the reduced-electrodes study, we also evaluated full VCIS processors with additional subjects. The results are presented in Fig. 4. The initial findings for SR2 are repeated in the top panel. Scores for subjects SR10 and SR13 are shown in the middle and bottom panels, respectively. The consonant tests for SR2 included 24 consonants with both male and female speakers, whereas the tests for SR10 and SR13 included 16 consonants. Tests with both male and female speakers were used for SR10, whereas only the male speaker was used for SR13.

The processors implemented for SR13 used the five apical electrodes only, because stimulation of basalmost electrode 6 elicited a somatic sensation at levels just above auditory threshold. Each subject was fitted with an 11 channel VCIS processor. The 11 channel processors for SR2 and SR10 used interior virtual channels, as illustrated in Fig. 2. The processor for SR13 used four interior virtual channels (corresponding to the positions between the five available electrodes) and two exterior virtual channels, formed with a principal pulse on the apicalmost or basalmost electrode paired with a half-amplitude reversed-polarity pulse on the adjacent electrode (i.e., on electrode 2 for a principal pulse on apicalmost electrode 1, or on electrode 4 for a principal pulse on basalmost electrode 5).

In general, the results do not demonstrate an advantage of VCIS processors. Scores from the consonant tests are not statistically different for any of the subjects. Results from the open-set tests are mixed, with somewhat better scores for VCIS in some cases (e.g., the NU-6 test for SR2 and the CID test for SR10) and for CIS in others (e.g., the NU-6 test for SR10). The only large difference between processors is in the NU-6 scores for SR13, where the score for the CIS processor is clearly better than the score for the VCIS processor.

Although the speech reception scores for the two types of processor were similar, each of the subjects expressed a strong preference for the VCIS processor. Each them said that the VCIS processor sounded more natural and seemed more intelligible than the CIS processor. SR2 and SR13 also compared the two processors for listening to music, and both said the VCIS processor produced a richer and more natural sound than the CIS processor.

Discussion

Present implementations of VCIS processors offer no obvious advantage over CIS despite some very encouraging initial results, and despite the strong preference for VCIS expressed by all three subjects. It is possible that we have not selected the best tests to demonstrate a difference between processors, as suggested by the anecdotal remarks of the subjects. For example, a difficult test of vowel identification might demonstrate a difference between processors with sparse *versus* dense spatial representations (e.g., CIS *versus* VCIS, where each of the processors use the same number of electrodes). In initial tests of vowel identification, involving 12 different synthesized vowels of equal durations, SR2 obtained a higher score with a VCIS processor than with a CIS processor (percent correct identification was 82% with VCIS and 72% with CIS; Michael Dorman, personal communication to Wilson, 1992). Also, tests of music perception may demonstrate difference between processors. Studies of complex tone perception, as described in Quarterly Progress Report 4 for this project, are underway with subject SR2

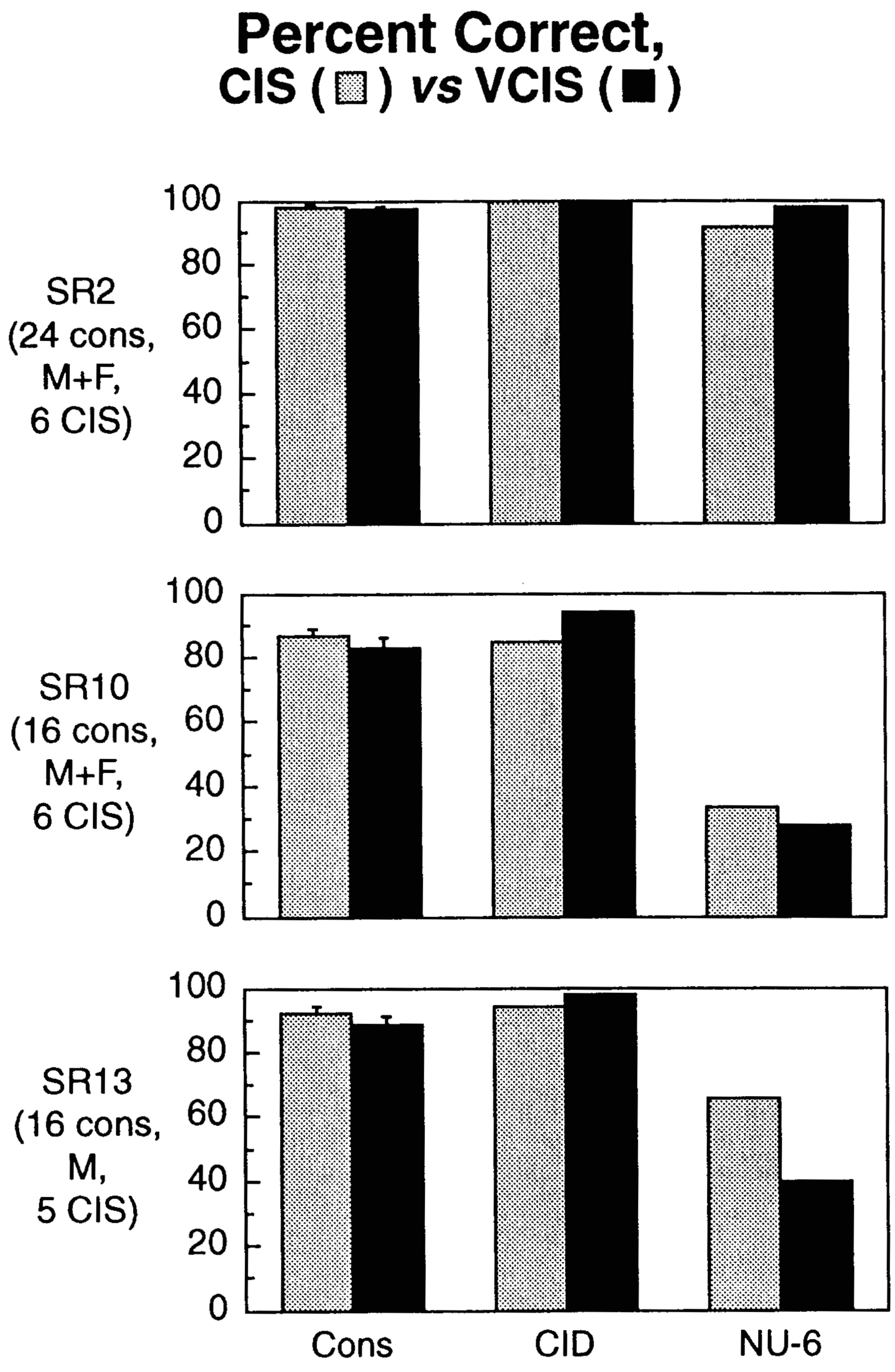


Fig. 4. Comparisons of CIS and VCIS processors for three subjects. Tests included identification of consonants in an /a/-consonant-/a/ context (Cons), recognition of key words in the Central Institute for the Deaf sentences of everyday speech (CID), and recognition of monosyllabic words from Northwestern University Auditory Test 6 (NU-6).

using both VCIS and CIS processors.

We are not quite ready to discontinue our studies with VCIS processors. Evaluation of VCIS with different tests seems warranted. Also, we note that alternative implementations of VCIS processors may be superior to the present implementations. For example, selective use of single-electrode and multiple-electrode channels may allow implementation of a processor with a relatively large number of channels (e.g., 7 or 8) with a high degree of perceptual distinctness among channels. We are exploring the potential of such alternative implementations with psychophysical studies of channel scaling and channel identification. As indicated in our last Quarterly Progress Report, we also are assessing the spatial patterns of neural excitation produced with single-electrode and multiple-electrode stimulation using a forward masking technique. Results from those studies should indicate whether additional information can be provided with the selective use of virtual channels or with types of virtual channels different from those used in the present implementations of VCIS processors.

V. Plans for the Next Quarter

Our plans for the next quarter include the following:

1. Extended studies with Ineraid subjects SR2 (three weeks) and SR3 (two weeks), primarily to continue our measures of intracochlear evoked potentials. The studies with SR3 also will include measures of speech reception with single-channel processors, for comparison with evoked potential and psychophysical results obtained at the University of Iowa (by Paul Abbas and Carolyn Brown) and in our laboratory for single electrodes with SR3's implant. In addition, studies with SR2 will include (a) further evaluation of the implant system proposed for use in China, (b) evaluation of new speech test materials from Indiana University, which may offer increased sensitivity for high-performance subjects like SR2, and (c) evaluation of VCIS processors using a reduced number of CIS and VCIS channels, selected to maximize perceptual separability among channels.
2. Continued interaction with the groups at the Massachusetts Eye & Ear Infirmary in Boston and the Hôpital Cantonal Universitaire in Geneva, Switzerland, to develop a portable processor for use in research studies.
3. Initiation of studies with the first patient implanted with the experimental Nucleus device, which includes a percutaneous connector in conjunction with the standard Nucleus electrode array.
4. Presentation of project results in invited lectures at the *5th Symposium on Cochlear Implants in Children* (New York, NY, February 4 and 5), Indiana University School of Medicine (Indianapolis, IN, March 9), and the *Annual Carolinas Audiology Conference* (Asheville, NC, April 1).
5. Continued preparation of manuscripts for publication.

VI. Acknowledgments

We thank the three subjects of the studies described in this report for their enthusiastic participation and generous contributions of time. We also are grateful to M.F. Dorman and C.C. Finley, who helped us with various scientific aspects of the work.

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Appendix 1

Summary of Reporting Activity for the Period of

November 1, 1993 through January 31, 1994

NIH Project N01-DC-2-2401

Reporting activity for the last quarter included two invited lectures. Citations are listed below.

Lawson DT: Cochlear implants: Current research. Presented at the *5th Annual Audiology Videoconference*, sponsored by the Mayo and Sheldon Reese Foundations, Jacksonville, FL, November 6, 1993.

Wilson BS: Review of speech processor studies. Presented at the University of Iowa, Department of Otolaryngology -- Head & Neck Surgery, Iowa City, IA, January 18, 1994.