Fourth Quarterly Progress Report

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Speech Processors for Auditory Prostheses

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I. Introduction

The main objective of this project is to design, develop, and evaluate speech processors for implantable auditory prostheses. Ideally, such processors will represent the information content of speech in a way that can be perceived and utilized by implant patients. An additional objective is to record responses of the auditory nerve to a variety of electrical stimuli in studies with patients. Results from such recordings can provide important information on the physiological function of the nerve, on an electrode-by-electrode basis, and also can be used to evaluate the ability of speech processing strategies to produce desired spatial or temporal patterns of neural activity.

Work in this quarter included:

- Ongoing studies with Ineraid subject SR2, who now is working with us for one or two days each week. Studies in this quarter included continuation of an extensive series of measures to evaluate effects of manipulations in rate of stimulation and in the cutoff frequency for the lowpass filters in the envelope detectors in CIS processors. The measures have included consonant identification in quiet and at the speech-to-noise ratios of +15 and +10 dB.
- Studies with Ineraid subject SR9, for the weeks beginning August 2 and August 9. The studies included an extensive series of measures to evaluate effects of manipulations in rate of stimulation and in the cutoff frequency for the lowpass filters in the envelope detectors in CIS processors, as with SR2 above. The measures for SR9 included consonant identification and recognition of CUNY sentences in quiet. The studies with SR9 also included measures of consonant identification for CIS processors using a wide range of compression functions. Tests of speech presented in conjunction with noise were not conducted with SR9, as even small amounts of noise greatly depress her scores and often produce floor effects in the data.
- Discussions with Chris van den Honert from Cochlear Corporation, during a visit by him to RTI on July 12.
- Continued development of an Access database of processor designs and study results, to bring this information together in one place for fast access and in a structure that will allow retrieval of prior designs and results on the basis of shared attributes and parameter values.
- Initial development of additional databases, for psychophysical and evoked potential studies.
- Interviews with candidates to fill a DSP/Electrical Engineer position on the team.
- Presentation of project results in three invited lectures and one poster at the *1999 Conference on Implantable Auditory Prostheses*, held in Pacific Grove, CA, August 29 through September 3.
- Preparation for studies in the next quarter with patients having bilateral COMBI 40+ implants or bilateral CI24M implants. The preparation included visits by consultant Marian Zerbi to work with Finley in completing an interface system for simultaneous laboratory control of two CI24M implants. Zerbi is continuing ongoing work to implement new processing strategies that are designed to preserve sound localization cues through coordinated stimulation of the two sides.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

In this report we present results from prior studies with three subjects having the same type of cochlear implant on both sides. In Quarterly Progress Report 1 for the current contract we described studies with these subjects to measure sensitivities to timing and amplitude differences between stimuli delivered to the two sides. In this report we present speech reception studies conducted with the same subjects (studies with subject NU-4 also have been described in QPR 5 of our prior project and in Lawson *et al.*, "Bilateral cochlear implants controlled by a single speech processor," Am J Otol 19: 758-761, 1998). These studies included evaluation of various speech processor designs, some of which presented stimuli across the two sides. An additional section in the present report provides an update on the longitudinal studies described in QPR 2 for this project. Results from other studies indicated in the list of activities above will be presented in future reports.

II. Speech reception with bilateral cochlear implants

Coordinated stimulation of bilateral cochlear implants might support a useful representation of the interaural timing and amplitude cues used by listeners with normal hearing to lateralize sounds in the horizontal plane. An ability to lateralize and separate sources of sound allows listeners to attend to a desired talker in environments with competing talkers or noise from other directions. The signal-to-noise advantages of binaural hearing can be quite large.

An alternative approach for coordinated stimulation of bilateral implants might be to utilize additional electrodes, compared with the unilateral case, to (a) increase the number of effective channels, (b) increase rate of stimulation for a given number of channels, or (c) reduce electrode interactions for a given number of channels and rate of stimulation. In this alternative approach, no attempt would be made to represent or preserve interaural timing and amplitude cues.

Either approach might confer important advantages to recipients of bilateral implants. Some patients might enjoy the greatest advantage with one of the approaches, while others might benefit more from the other approach. For example, a patient with poor sensitivities to interaural cues might not receive much benefit from the first approach, aimed at representation of such cues, but might well benefit from one or more of the changes in processing supported through use of the second approach.

In addition, even uncoordinated stimulation of bilateral implants, using independent processors for the two implants, might be better than stimulation of either implant alone. Such independent processors would be expected to present redundant or strongly overlapping information across the two sides. Presentation of redundant information could be helpful for listening to speech in adverse situations. Independent processors also might preserve a representation of interaural amplitude differences, especially if the microphones for the two sides are at ear level, even while not preserving interaural timing differences.

In our view, the key questions in research on bilateral implants include the following:

- Do recipients of bilateral implants have access to the principal binaural cues of interaural timing and amplitude differences?
- If so, can coordinated stimulation of the two sides restore binaural hearing and the signal-to-noise advantages associated with binaural hearing?
- Can bilateral implants be exploited in other ways, *e.g.*, through use of additional distinct electrodes?
- Can independent processors confer any advantage, *e.g.*, through presentation of redundant information to the two sides or through a partial representation of interaural amplitude differences?

We have begun to address some of these questions in studies with three subjects having the same type of cochlear implant on both sides.

Sensitivities to interaural timing and amplitude differences

Measures of sensitivities to interaural timing and amplitude differences were presented in Quarterly Progress Report 1 for the current contract. Tables 1 and 2 provide summaries of the results. Table 1 shows the measured sensitivities to interaural timing differences (ITDs) for our three subjects and also for one subject studied at the Massachusetts Eye and Ear Infirmary (Long

Table 1. Sensitivities to interaural time delays (ITDs) between trains of pulses delivered to pitch- and loudness-matched pairs of electrodes.

Laboratory	Subject	Minimum ITD
RTI	NU-4	150 µs
	ME-2	450 µs, 40 pulses/s > 1 ms, other conditions
	NU-5	50 µs or less
MEEI	1	150-200 µs
Melbourne	P1	1 ms
	P2	500 µs, 200 pulses/s > 1 ms, other conditions

Table 2. Sensitivities to interaural amplitude differences (IADs) between trains of pulses presented simultaneously to pitch-matched pairs of electrodes.

Subject	Clinical Units	Fraction of DR
NU-4	1 (best) 4 (worst among 3 pairs)	1/75
ME-2	5	1/30
NU-5	1 3 (worst among 4 pairs)	1/75

et al., 1998 and 1999) and for two subjects studied at the University of Melbourne (van Hoesel *et al.*, 1993; van Hoesel and Clark, 1995 and 1997). As described in detail in our QPR 1, subject NU-4 has a full insertion of a Nucleus CI-22 implant on one side and a partial insertion of a CI-22 implant on the other side; subject ME-2 has full insertions of Med El COMBI 40 implants on both sides; and subject NU-5 has full insertions of Nucleus CI24M implants on both sides. The subject in the MEEI study has an Ineraid implant on one side and a Clarion implant on the other side. The subjects in the University of Melbourne study both have Nucleus 22 implants on both sides.

Sensitivities to ITDs have been measured using bilateral pairs of electrodes that elicit the same pitch and loudness percepts. Three such pairs were included in our studies with NU-4, and four such pairs were included in our studies with NU-5. One pair was included in the studies with ME-2. Multiple pairs of pitch- and loudness-matched electrodes have been included in the studies of Long *et al*. (1998) and van Hoesel and Clark (1997). In all studies trains of unmodulated pulses were delivered to the two implants (some of the studies also used additional stimuli, such as sinusoidally amplitude modulated trains of pulses). For measures of sensitivity to ITDs, one train was delayed with respect to the other.

As is evident from Table 1, a wide range of sensitivities is found for these subjects. Subject NU-5 was able to lateralize reliably a sound image toward the ear with the leading pulse train at the delay of 50 µs. We were unable to evaluate possible sensitivity to delays below 50 µs because that was the smallest delay our equipment and controlling software could support at the time of the studies.

In contrast, subject ME-2 in our studies, and both subjects in the Melbourne studies, had much poorer sensitivities. Under a particular condition, subject ME-2 had a sensitivity of 450 µs, but much worse sensitivities for other conditions. Similarly, subject P2 in the Melbourne studies had a sensitivity of approximately 500 µs at the pulse rate of 200/s, but much worse sensitivities for the other tested rates (50, 100 and 300 pulses/s). Subject P1 had quite poor sensitivities for all tested conditions (including two pitch- and loudness-matched pairs of electrodes and the rates of 50, 100, 200 and 300 pulses/s).

The maximum delay between ears for a 9 cm head in a sound field is 680 µs. Thus one would expect that a sensitivity to ITDs of 680 µs or less is necessary for utility of such cues in real acoustic environments (in the absence of some special processing to exaggerate ITD cues). A time difference of 50 µs, for instance, corresponds to an incidence from only about 5 degrees to one side of the midline. The intermediate sensitivities demonstrated by subject NU-4 in our studies and the subject in the MEEI studies correspond to an incidence from about 15 degrees to one side. Even sensitivities as poor as 450 µs, which correspond to incidence angles of about 45 degrees, might be of some use in real acoustical environments.

A good sensitivity to interaural timing differences indicates that central auditory processing of binaural inputs is intact. Because differences in loudness between the two sides can be determined with monaural processing, sensitivities to interaural amplitude differences do not necessarily demonstrate integrity of the binaural system.

In our studies, subjects NU-5 and NU-4 had good sensitivities to ITDs. Subject ME-2 had only poor or quite poor sensitivities depending on the stimuli used. These and the other findings summarized in Table 1 suggest that at least some recipients of bilateral implants have functional binaural systems.

Sensitivities to IADs have been measured in our studies by determining the point at which a reduction in the amplitude of pulses for one of the pulse trains shifts a sound image reliably toward the ear receiving the unaltered stimulus. Table 2 shows generally good sensitivities to interaural amplitude differences for each of our three subjects. Subjects NU-4 and NU-5 could reliably lateralize a sound image with the smallest possible change in amplitude between the two sides (one clinical unit for the CI22 or CI24M devices, respectively), for at least one pair of pitch-matched electrodes. This corresponded to about 1/75th of the dynamic range for each of these subjects. Subject ME-2 required a greater change in amplitude for reliable judgments (five clinical units for the COMBI 40 device, which corresponded to about 1/30th of his dynamic range). In all cases, only relatively small changes in the amplitude were required for a reliable shift in the sound image toward the side with the greater amplitude compared to the loudness balanced control condition.

As noted above, a good sensitivity to IADs might be achieved by purely monaural processing. Subjects with good sensitivities to IADs but poor sensitivities to ITDs may not enjoy great benefits from strategies designed to restore binaural hearing.

Integration of inputs from the two sides

We have conducted a variety of studies to evaluate potential benefits of various strategies for assigning channels across bilateral implants. The questions included (a) whether bilateral stimulation might be distracting to a subject or otherwise reduce the performance of processors using bilateral stimulation compared with processors using unilateral stimulation; (b) whether an additional contralateral channel might be equivalent to an additional ipsilateral channel in terms of speech reception performance; and (c) whether the availability of bilateral electrodes under control of a single speech processor might support higher speech reception scores through changes such as an increase in the number of effective channels or a reduction in electrode interactions for a fixed number of channels. In these particular studies, no attempt was made to represent the lateralization cues of interaural timing and amplitude differences.

Results from studies with subject NU-4 are presented in Figs. 1 and 2. Fig. 1 shows consonant identification scores for various assignments of channels to electrodes between the two implants. Results for unilateral stimulation are presented in the first two bars, for stimulation of the left (processor 11) and right implant (processor 12), respectively. The electrodes selected for each side elicited similar ranges of pitch percepts and spanned the same cochlear distance.

The two rightmost bars show results for assignments of channels across the implants. In one variation channels 1, 3 and 5 were directed to the left implant and channels 2, 4 and 6 were directed to the right implant. In the other variation the converse was done, with channels 1, 3 and 5 directed to the right implant and channels 2, 4 and 6 directed to the left implant.

The scores for either processor using bilateral stimulation are significantly higher than for either processor using unilateral stimulation. The left unilateral processor produced a higher score than the right unilateral processor.

The comparisons in Fig. 1 indicate an advantage of "interlacing" channels across the two sides. For a fixed number of channels, and for the same distance across the electrodes addressed in the electrode array(s), such interlacing increases the distance between stimulated electrodes on each side, and halves the aggregate stimulation rate to each ear. (The rate of stimulation on each active electrode, of course, remains constant.) This in turn may reduce electrode interactions.

Figure 2 shows results for additional assignments of channels within or across the implants. In the leftmost processor (processor 5) six channels are assigned to more widely-spaced electrodes in the left implant. In the next processor (processor 6) those same channels are assigned across the implants, with channels 1-3 directed to the same electrodes in the left implant and channels 4-6 directed to similarly spaced electrodes in the right implant. In the third and fourth processors eight channels are assigned to widely-spaced electrodes in the left implant (processor 10) or across the two implants (processor 13). As in the second processor, the channel assignments in the fourth processor are equally divided between implants, with channels 1-4 directed to the left implant and with channels 5-8 directed to the right implant.

The scores for the two six-channel processors are not statistically different; nor are the scores for the two eight-channel processors. This shows that speech reception is not damaged even when the represented spectrum of speech sounds is split at the middle between the two implants.

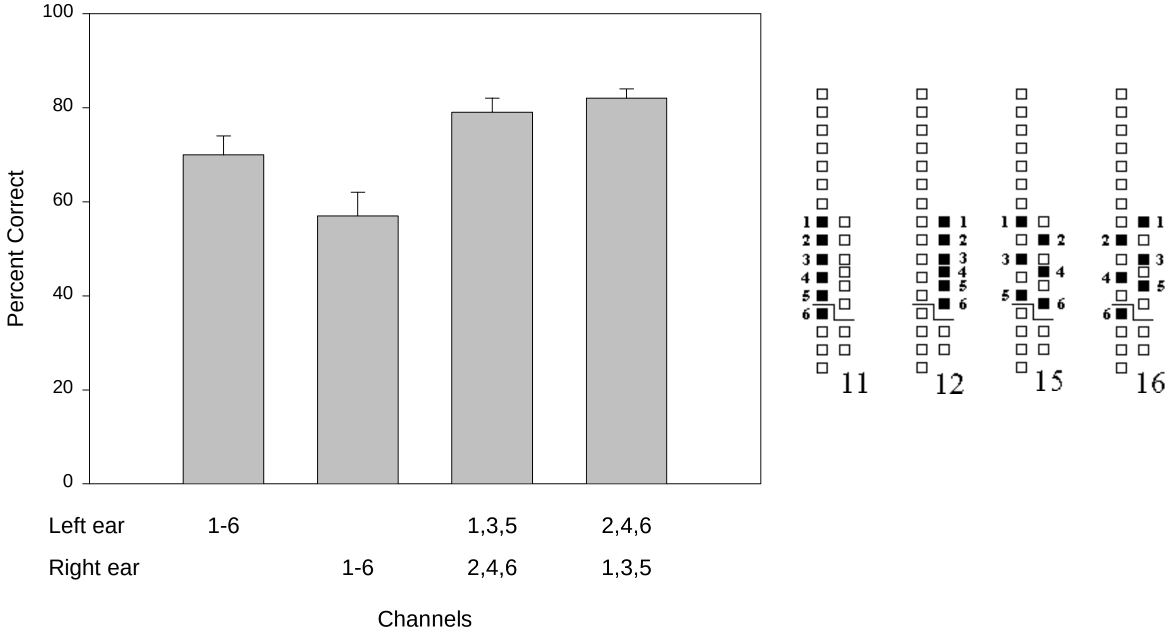

Fig. 1. Results from tests of consonant identification with subject NU-4. The tests included 16 consonants presented from recordings in randomized orders and in an /a/-consonant-/a/ context. Multiple exemplars of the test tokens were produced by a single male talker. The manipulation in this series of tests was channel-to-electrode assignments for 6-channel CIS processors, as indicated in the right panels. Processors 11 and 12 delivered their outputs to one implant only, and processors 15 and 16 delivered their outputs across the two implants. All processors used the rate of 480 pulses/s/electrode, the pulse duration of 80 µs/phase, and represented an overall frequency range of 350 to 5500 Hz. The stimuli for each channel were delivered in a staggered update order to bipolar pairs of electrodes in the Nucleus-22 implants. The squares in the right panels indicate, along the vertical direction, relative pitch ranking of available "bipolar-plus-one" pairs on both sides. Filled squares indicate those electrode pairs assigned to processor channels in each case, and are labeled by channel numbers ascending from the lowest bandpass center frequency to the highest. Basal positions along the electrode arrays are toward the bottom of each diagram, and apical positions are toward the top; thus perceived pitch is higher toward the bottom. [For a more complete explanation of the diagrams in the right panels, see QPR5 for the previous contract.] Note the consequences of the partial insertion of NU-4's electrode array on the right side.

While the aggregate stimulation rate to each ear is again halved, the distance between stimulated electrodes within an implant is not changed with unilateral *versus* bilateral manipulations in the processors of Fig. 2. Thus, a reduction in the electrode interactions might not be expected for either the six channel or eight channel comparison.

Anecdotally, the subject was well aware of the bilateral nature of the processors stimulating both implants. However, she had no greater difficulty in recognizing speech compared with the control processors stimulating one implant only.

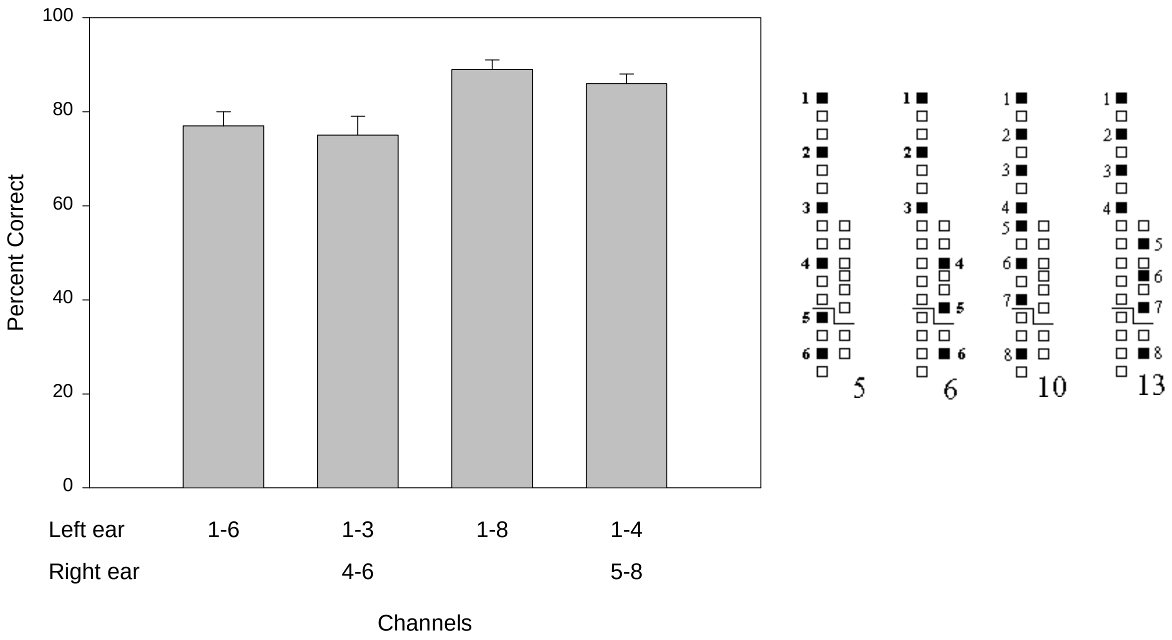

Fig. 2. Additional results from tests of consonant identification with subject NU-4. The manipulation in these tests was channel-to-electrode assignments for 6- and 8-channel CIS processors, as indicated in the right panels. The outputs for the six channels of processor 5 were delivered to the left implant only. The selected electrode pairs were more widely spaced than those of processor 11 in Fig. 1. Processor 6 was identical to processor 5 except in the assignment of channels to electrodes, in that the outputs of channels 4-6 were redirected to the right implant. Similarly, the outputs of all eight channels in processor 10 were delivered to the left implant, and processor 13 was identical except that the outputs of channels 5-8 were redirected to the right implant. All processors used a rate of 480 pulses/s/electrode, a staggered update order, a pulse duration of 80 μs/phase, and an overall frequency range of 350 to 5500 Hz. The organization of the right panels is described in the caption for Fig. 1.

An additional aspect of the results in Fig. 2 is that the eight-channel processors produced higher scores than the six-channel processors. This suggests the possibility that further increases in the number of channels might produce further increases in speech reception performance. As described in QPR 1 for the current contract (page 17), this subject can rank a total of 14 stimulation sites across the two implants according to pitch. This compares with a total of 13 such sites for the left implant only and 4 such sites for the right implant only. The additional distinct site of stimulation available with bilateral stimulation, as compared with stimulation of the left implant only, might be helpful. Also, a number of channels between 8 and 13 may optimize performance, through a good tradeoff between the number of channels and electrode interactions. For example, a 10-channel processor might provide a useful increment in the number of channels while still minimizing electrode interactions (with choices of channel-to-electrode assignments that maximize the distances between stimulating electrodes in each implant). We plan to evaluate these possibilities in future studies with this subject and in future studies with other subjects.

Similar studies also have been conducted with subject ME-2 to evaluate whether assignment of a fixed number of channels to electrodes across implants produces a decrement in performance compared with assignment of those channels to electrodes within one implant only. The results are presented in Fig. 3. The first two bars show scores for stimulation of the right and left implants only, using 6-channel CIS processors. Channels 1-6 were assigned to electrodes 2, 3, 4, 6, 7 and 8, respectively, for both processors. Bars 3-6 show the scores for various assignments of the six channels across the two implants. The processors of bars 3 and 4 split the channels, with channels 1-3 directed to electrodes in the apical half of one of the implants and channels 4-6 directed to electrodes in the basal half of the other implant. Bars 5 and 6 show scores for alternating assignments of channels to electrodes across the implants. The processor of bar 5 directed the odd-numbered channels to electrodes 2, 4 and 7 in the left implant, and the even-numbered channels to electrodes 3, 6 and 8 in the right implant. The processor of bar 6 did the converse. The final condition involved two identical six-channel processors, stimulating electrodes 2, 3, 4, 6, 7 and 8 in each implant.

Comparison of the scores for stimulation of either implant only indicates that stimulation of the right implant is better than stimulation of the left implant. In addition, comparisons among the scores for processors that present six channels across implants show a sensitivity to the way in which channels are assigned to electrodes. The processor that directs channels 1-3 to electrodes in the left implant (third bar in Fig. 3) is better than the processor that directs those channels to electrodes in the right implant (fourth bar). However, the processor that directs the odd-numbered channels to electrodes in the left implant (fifth bar) is not statistically better than the processor that directs those channels to electrodes in the right implant (sixth bar). These findings suggest that inclusion of one or more of the electrodes in the right implant, or use of certain combinations of electrodes in the right implant, may degrade performance.

The score for the bilateral processor that directs channels 1-3 to the left implant (bar 3), and the score for the bilateral processor that directs the odd-numbered channels to electrodes 2, 4 and 7 in the left implant (bar 5), are not statistically different from the score for the processor that stimulates the left implant only (bar 1). This shows that inputs from the two sides can be combined, without producing a decrement in performance compared with the performance of the better unilateral implant.

Unlike the results for subject NU-4, increasing the distance between stimulated electrodes within each implant (through assignment of alternating channels to each side) did not produce an improvement for ME-2. Possibly, electrode interactions were already low with the 2.7 mm spacing of adjacent electrodes in the Med El implants used by ME-2. A greater spacing may not have produced a significant reduction in interactions and therefore may not have enhanced the representation of channel-related cues. In contrast, the distance between adjacent bipolar electrode pairs in the Nucleus implants used by NU-4 is only 0.75 mm. Reductions in interactions would seem more likely with the tested increases in the distance between stimulating pairs in the Nucleus implants than with the tested increases in the distance between stimulating monopolar electrodes in the Med El implants.

In the final condition of Fig. 3 both implants were stimulated with identical 6-channel processors. The score for this condition was not statistically higher than the score for stimulation of the left implant only (or for other conditions in Fig. 3). The presentation of redundant information to the two sides did not improve speech reception scores, at least for conditions of these tests.

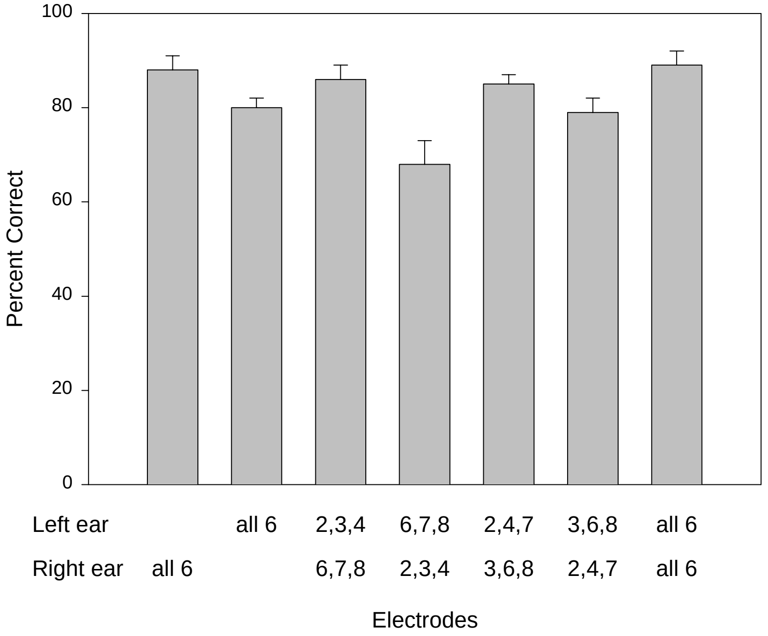

Fig. 3. Results from tests of consonant identification with subject ME-2. The tests included 16 consonants presented from recordings in randomized orders and in an /a/-consonant-/a/ context. Multiple exemplars of the test tokens were produced by a single male talker. The manipulation in this series of tests was channel-to-electrode assignments for various 6-channel CIS processors, including one dual set of 6-channel processors. The first two processors delivered their outputs to one implant only. Electrodes 2, 3, 4, 6, 7 and 8 were used in both cases. The third processor delivered the outputs of its channels 1-3 to apical electrodes 2, 3 and 4 on the left and outputs of channels 4-6 to basal electrodes 6, 7 and 8 in the right implant. The fourth processor did the converse, delivering the outputs of its channels 1-3 to apical electrodes 2, 3 and 4 on the right and the outputs of channels 4-6 to basal electrodes 6, 7 and 8 on the left. The fifth and sixth processors "interlaced" channels across the two sides, increasing the distance between the selected electrodes for either side. The fifth processor delivered the outputs of channels 1, 3 and 5 to electrodes 2, 4 and 7 on the left and outputs of channels 2, 4 and 6 to electrodes 3, 6 and 8 on the right. The sixth processor did the converse. The final tested variation involved two identical 6-channel processors delivering outputs to electrodes 2, 3, 4, 6, 7 and 8 in both implants. All processors used a rate of 1000 pulses/s/electrode, a pulse duration of 70 µs/phase, an overall frequency range of 350 to 5500 Hz, and fullwave rectifiers and 200 Hz lowpass filters in the envelope detectors. The stimuli for each channel were delivered in a staggered update order to monopolar electrodes in the COMBI 40 implants. The electrodes are numbered in these implants from apex to base (opposite to the numbering for the Nucleus implants). The identifying numbers for the ME-2 processors referred to in this figure are -- from left to right -- 13, 14, 5, 7, 9, 11, and 15.

Like subject NU-4, ME-2 did not experience any difficulty in combining inputs from the two sides. He knew when both implants were activated, but also described unitary percepts of speech sounds. His scores in tests of consonant identification were not different among unilateral stimulation of his better (left) implant and two of the tested variations of bilateral stimulation, that assigned either alternating channels to each implant or directed the outputs of channels 1-3 to one implant and the outputs of channels 4-6 to the other implant.

Results from the above studies with NU-4 and ME-2 demonstrate that inputs from the two sides can be integrated into single auditory percepts and also that presentation of channels across implants can be equivalent to or better than unilateral stimulation with the same number of channels, even when information is allocated between the two sides in arbitrary ways. In these studies the assignments of channels to electrodes for the bilateral processors did maintain a monotonic ordering of increasing pitch with increasing channel number.

A question not addressed by the results from the studies with NU-4 and ME-2 is whether a monotonic ordering must be maintained to support speech reception scores that are at least as good as unilateral stimulation with the same number of channels. Possibly, binaural processing might allow separation of channels on bases other than pitch.

In studies with subject NU-5 we asked this question by comparing 8-channel processors that assigned channels across the two sides to either produce distinct pitches among all of the selected electrodes or to produce the same pitches for channels 1 and 2, the same pitches for channels 3 and 4, and so forth. This second variation of an 8-channel processor used pitch-matched pairs of electrodes between the two implants.

The results are presented in Fig. 4. The first variation of 8-channel processors is labeled as "8 ch distinct" and the second variation is labeled as "8 ch matched pairs." As a control, four-channel processors stimulating either the left or right implants also were tested. The tests included consonant identification in quiet and at the speech-to-noise ratios of +10 and +5 dB.

As is evident from the figure, the first of these 8-channel processors produced significantly higher scores than the second processor for consonant identification in quiet and consonant identification at both speech-to-noise ratios. This indicates that, for a given number of channels, speech reception scores may be maximized through channel-to-electrode assignments that produce distinct pitches among all of the electrodes, and that a lateral distinction without an associated pitch difference is not as effective as a pitch distinction.

The additional results in Fig. 4 also indicate that a four-channel processor stimulating one implant only can be equivalent to the 8-channel processor with channel-to-electrode assignments using matched pairs of electrodes between the implants on both sides. This suggests that the central auditory system integrates the information presented to the pitch-matched pairs of electrodes into a single percept. Thus, for example, the information in the bandpass of channel 1, presented to an electrode in one implant, may be combined with the information in the bandpass of channel 2, presented to an electrode in the other implant that elicits the same pitch percept. Such combinations would produce a total of only four information channels for the "8 channel, matched pairs" condition. Apparently, information is sorted according to pitch or pitch regions and not according to side of stimulation, at least for identification of consonants by this subject.

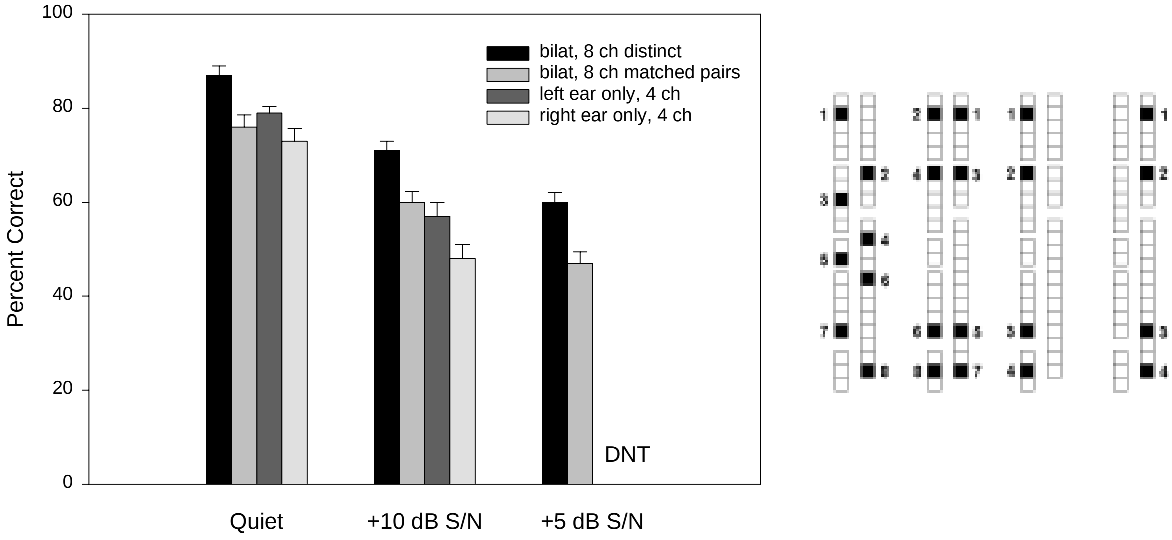

Fig. 4. Results from tests of consonant identification with subject NU-5. The tests included 24 consonants presented from recordings in randomized orders and in an /a/-consonant-/a/ context. Multiple exemplars of the test tokens were produced by a male talker. The consonants were presented in quiet or in conjunction with CCITT noise, which has a spectrum that matches the long-term spectrum of speech. CIS processors were used. Two of the processors presented the outputs of eight channels in an alternating order across the implants. The first of these used a set of eight electrodes for which trains of unmodulated pulses elicited eight distinct pitch percepts. In the second of these processors the outputs for successive channels were presented to members of pitch-matched pairs of electrodes on the two sides, with only four distinct pitches represented overall. The third and fourth processors were four-channel designs and presented their outputs to the left and right subsets, respectively, of the electrodes used in the second eight-channel processor. The squares in the right panels indicate, along the vertical direction, relative pitch ranking of available monopolar electrodes in the CI24M implants. Filled squares indicate those electrodes assigned to processor channels in each case, and are labeled by channel numbers, ascending from the lowest bandpass center frequency to the highest. Basal positions along the electrode arrays are toward the bottom of each diagram, and apical positions toward the top; thus perceived pitch is higher toward the bottom. All processors used a rate of 750 pulses/s/electrode, a staggered update order, a pulse duration of 25 µs/phase, an overall frequency range of 350 to 5500 Hz, and fullwave rectifiers and 200 Hz lowpass filters in the envelope detectors. The identifying numbers for the NU-5 processors referred to in this figure are -- from left to right in each group -- 12, 13, 10, and 9.

Independent processors

One of the key questions in research on bilateral implants is whether use of independent processors for the two sides is any better than use of a single processor, stimulating only one of the implants. This question was addressed in studies with subjects ME-2 and NU-5.

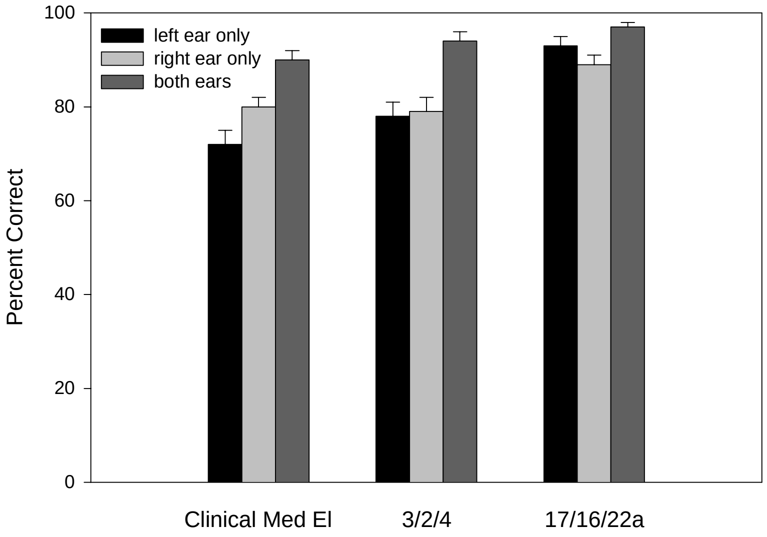

Fig. 5. Results from tests of consonant identification with subject ME-2. The tests included 16 consonants presented from recordings in randomized orders and in an /a/-consonant-/a/ context. Multiple exemplars of the test tokens were produced by a male talker. CIS processors were used. The clinical Med El processors for the two implants each used seven channels and 40 µs/phase pulses. Laboratory ME-2 processors 3, 4 and 5 each used 6 channels and 70 µs/phase pulses, presented at the rate of 1000 pulses/s/electrode. Laboratory ME-2 processors 17, 16 and 22a each used 6 channels and 100 µs/phase pulses, presented at the rate of 823 pulses/s/electrode. Each of the laboratory processors assigned channels 1-6 to electrodes 2, 3, 4, 6, 7 and 8 in the one implant used for unilateral stimulation or in both implants for bilateral stimulation. A staggered order of electrode stimulation was used for each of the laboratory processors.

Results for ME-2 are presented in Figs. 5 and 6. Figure 5 shows scores from tests of consonant identification for stimulation of the left implant only with one of the subject's clinical Med El (CIS) processors, stimulation of the right implant only with the second of the subject's Med El processors (programmed separately for that implant), and stimulation of both implants with both processors. In this last condition, the processors run independently of each other and may not preserve fine timing differences between the ears that would be present in normal hearing.

Figure 5 also shows scores for laboratory processors applied in these three ways: stimulation of the left implant only, stimulation of the right implant only, and stimulation of both implants with two separate processors. Processors 3, 2 and 4 presented 70 µs/phase pulses at the rate of 1000 pulses/s/electrode, and processors 17, 16 and 22a presented 100 µs/phase pulses at the rate of 823 pulses/s/electrode. The clinical Med El processors used seven channels and electrode positions for each implant, whereas the laboratory processors used six channels and electrode positions for each implant.

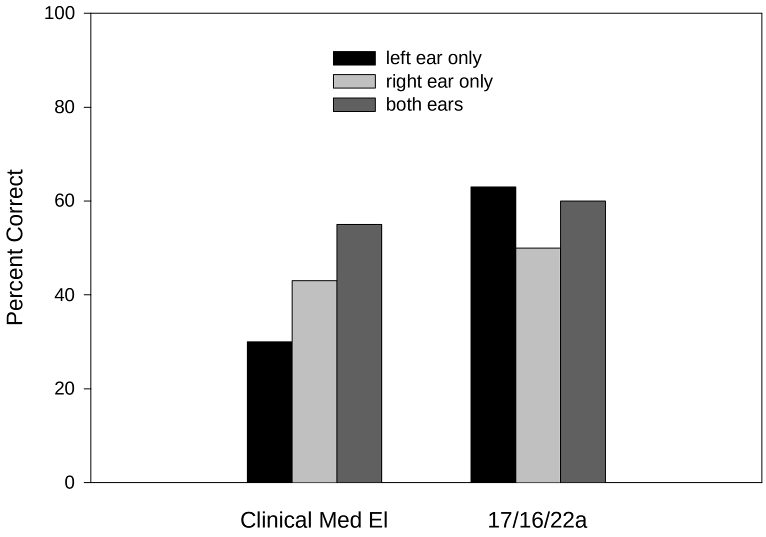

Fig. 6. Percent-correct scores for the recognition of Freiburger monosyllabic words by subject ME-2. The processors are the same as those described in the caption for Fig. 5.

The results show that bilateral stimulation with independent processors can be better than stimulation of either implant alone. That is true for the pair of Med El processors, where scores are significantly higher than for stimulation of either implant alone. Also in the case of the Med El processors the score for right ear stimulation alone is significantly higher than the score for left ear stimulation alone.

Similarly, the score for stimulation of both implants with laboratory processor 4 is significantly higher than the scores for stimulation of the left or right implants only, with processors 3 and 2, respectively. Among processors 17, 16 and22a, the score for stimulation of both implants with 22a is significantly higher than the score for stimulation of the right implant only with processor 16. However, the score for bilateral stimulation with 22a is not significantly different from the score for stimulation of the left implant only with processor 17. Given the very high score for processor 22a, ceiling effects may have masked a possible difference between it and processor 17.

Scores from tests of monosyllabic word recognition for the clinical Med El processors and for laboratory processors 17, 16 and 22a are presented in Fig. 6. The scores for these tests mirror the scores for consonant identification, presented in Fig. 5. In both sets of data bilateral stimulation with the two Med El processors is better than stimulation of either implant alone, and unilateral stimulation of the right implant is better than unilateral stimulation of the left implant. Also, bilateral stimulation with laboratory processor 22a is better than unilateral stimulation of the right implant with processor 16, but not better than unilateral stimulation of the left implant with processor 17. The scores for monosyllabic words are in the sensitive range (*i.e.*, well below the ceiling) for each of these processors, reducing the possibility that a difference between processors 22a and 17 was masked by a ceiling effect in the tests of Fig. 5.

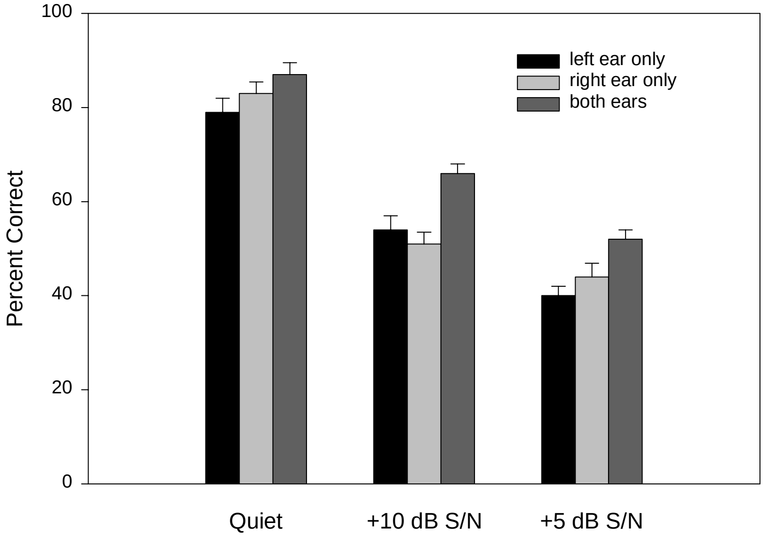

Fig. 7. Results from tests of consonant identification with subject NU-5, using clinical SPEAK processors for either or both implants, as indicated in the legend. The tests included 24 consonants presented from recordings in randomized orders and in an /a/-consonant-/a/ context. Multiple exemplars of the test tokens were produced by a male talker. The consonants were presented in quiet or in conjunction with CCITT noise, which has a spectrum that matches the long-term spectrum of speech.

These findings for ME-2 do not indicate any destructive effect of bilateral stimulation, that might be produced by the presentation of conflicting information between the two sides or an inability to integrate inputs from the two sides. In the comparisons involving the clinical Med El processors and those involving laboratory processors 3, 2 and 4, bilateral stimulation is clearly better than unilateral stimulation of either ear. In the comparison involving processors 17, 16 and R22a, bilateral stimulation is not worse than stimulation of the left implant only and is better than stimulation of the right implant only.

Results from tests with subject NU-5 are presented in Figs. 7 and 8. Figure 7 shows scores from tests of consonant identification for stimulation of the left implant only with one of the subject's clinical SPEAK processors, stimulation of the right implant only with the second of the subject's SPEAK processors, and stimulation of both implants with both processors. Again the processors run independently of each other. Because of the nature of the SPEAK processing strategy, and the use of pulse burst length to convey information between speech processor and implanted stimulator in the Nucleus devices, fine timing differences between the ears are not preserved. Figure 8 shows scores from additional tests for these same processor and implant conditions. The additional tests included recognition of monosyllabic CNC words, recognition of key words in HINT sentences, recognition of key words in CUNY sentences, and recognition of key words in additional CUNY sentences presented in conjunction with noise at the speech-to-noise ratio of +10 dB. These additional tests were conducted at the University of Iowa (data kindly provided by Rich Tyler, University of Iowa).

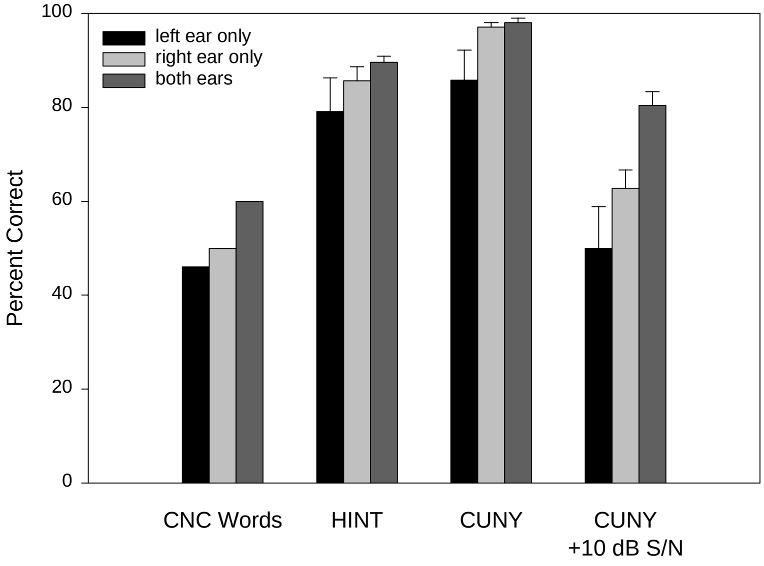

Fig. 8. Percent-correct scores for the recognition of CNC monosyllabic words and key words in the HINT and CUNY sentences by subject NU-5. The CUNY sentences were presented in quiet and in conjunction with noise, at the speech-to-noise ratio of +10 dB. The subject's clinical SPEAK processors were used for either or both implants, as indicated in the legend. These tests were conducted at the University of Iowa. (Data kindly provided by R. Tyler, University of Iowa.)

Scores from tests of consonant identification in quiet are not different among stimulation of either implant alone or bilateral stimulation. However, the scores from tests of consonant identification in noise show a large advantage of bilateral stimulation, at both speech-to-noise ratios.

Scores from the remaining tests (Fig. 8) also show an advantage of bilateral stimulation for speech reception in noise. In particular, recognition of CUNY sentences in competition with noise at the speech-to-noise ratio of +10 dB is better with bilateral stimulation than with stimulation of either implant alone. Also, recognition of the monosyllabic CNC words appears to be better with bilateral stimulation than with stimulation of either implant alone. The scores for HINT sentences presented in quiet are not different among stimulation of either implant alone or bilateral stimulation. The scores for CUNY sentences presented in quiet are not different between bilateral stimulation or stimulation of the right implant only. However, possible differences among processor and implant conditions may have been masked by likely ceiling effects in these tests (the scores for two of the conditions are close to 100 percent correct).

The findings for NU-5 indicate an equivalence or superiority of bilateral stimulation compared with stimulation of either implant alone. Bilateral stimulation appears to be especially helpful to this subject for listening to speech presented in competition with noise.

Summary

In response to the key questions listed at the beginning of this section, we now can say the following:

- Subjects with bilateral implants show a wide range of sensitivities to interaural timing differences, with some subjects having sensitivities that correspond to angles of sound incidence of 15 degrees or less from the midline.
- In general, sensitivities to interaural amplitude differences are good.
- We do not yet know whether coordinated stimulation of the two sides can restore binaural abilities for patients with good sensitivities to ITD and IAD cues.
- Recipients of bilateral implants can integrate information from the two sides, even when that information is allocated between the two sides in arbitrary ways, *e.g.*, odd-numbered channels on one side and even-numbered channels on the other side, or low frequency half of channels on one side and high frequency half on the other side.
- Independent processors, each stimulating one of the implants, can confer an advantage for at least some patients, especially in the presence of competing noise.

Future studies

Our plans for the near future include further studies with subjects NU-4 and NU-5 and initiation of studies with additional subjects having CI24M implants on both sides, referred to us from our colleagues at the University of Iowa, and with additional subjects having COMBI 40 or COMBI 40+ implants on both sides, referred to us from our colleagues at the Julius-Maximilians-Universität in Würzburg, Germany. The results collected to date are most encouraging. We now know that some patients have a good sensitivity to ITDs as well as a good sensitivity to IADs. Restoration of sound lateralization abilities, and the signal-to-noise advantages that accompany such abilities, is a realistic possibility for these patients. In future research we will evaluate that possibility. We also will collect results for additional subjects using the tests described in this report, including tests to evaluate various alternative representations of speech information with bilateral implants. Such alternative representations may be more effective for some patients than representations designed to preserve the interaural difference cues. Bilateral stimulation appears to offer important advantages to some patients even in the absence of any special processing. We expect that use of special processing, selected for the individual, may push scores higher.

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III. Update on longitudinal studies

In Quarterly Progress Report 2 for the current project, we reported on “Measures of performance over time following substitution of CIS for CA processors.” Included were results for five subjects: two subjects with relatively high levels of overall performance (SR3 and SR16, followed for 1135 and 589 days of chronic CIS processor use, respectively); one subject initially with a relatively low level of performance (SR10, fitted with a chronic CIS processor elsewhere and followed by us from day 466 through day 1512 of such use) but whose performance rose into the relatively high category during the course of our study; and two subjects with relatively low levels of overall performance (SR9 and SR15, followed for 372 and 531 days of chronic CIS use, respectively). We observed significant improvements in performance with experience for three of the five subjects -– all except SR9 and SR15.

Our study had followed subject SR9 for a significantly shorter time than any of the others and, near the end of that limited time, reversal of a processor change made at day 218 had produced an encouraging improvement in performance. We subsequently have had an opportunity to extend our longitudinal data for subject SR9 to 739 days of chronic CIS use, obtaining results that move that subject from one qualitative category to another and require modification of the longitudinal study’s summary findings.

In this update we shall describe only the latest results, place them in the context of earlier data for subject SR9, and then present a revised summary of the overall study’s findings.

Based on acute tests with a variety of designs, the first CIS processor given to SR9 for chronic use [labeled 7b] delivered 40 µs/phase pulses at the rate of 833 pulses/s to each of five channels, associated with the most basal five of SR9’s six Ineraid electrodes. [These and other processor parameters for all five studied subjects were listed in Table I of QPR 2 for the current project.] After 218 days of experience a sixth channel was added, utilizing the remaining electrode, without changing the stimulation rate on each channel. The resulting processor was labeled 9b1.

Figures 9, 10, and 11 display three measures of speech reception performance for SR9 with respect to the duration of her experience with a chronic CIS processor. In Fig. 9 the measure is percent correct identification of 16 consonants in /a/-consonant-/a/ context. In Fig. 10 the measure is percent overall information transmission derived from the same consonant identification data. Figure 11 shows percent correct word and phoneme scores for recognition of 50 monosyllabic words from standard NU6 lists. [More detail on these and other speech reception tests used in the longitudinal studies may be found in QPR 2 for the current project. These Figures 9, 10, and 11 are identical to Figures 10, 11, and 12 in QPR 2 except for the addition of subsequent data.]

The processor tested at day 0 was, of course, the five-channel 7b. After about 220 days of experience performance with that processor was remeasured, revealing unchanged scores for the female talker consonants and a decrease in male talker scores. Initial tests with the six-channel alternative 9b1 performed during the same laboratory visit by SR9 showed similar consonant recognition performance – a bit lower for male voice and a bit higher for female.

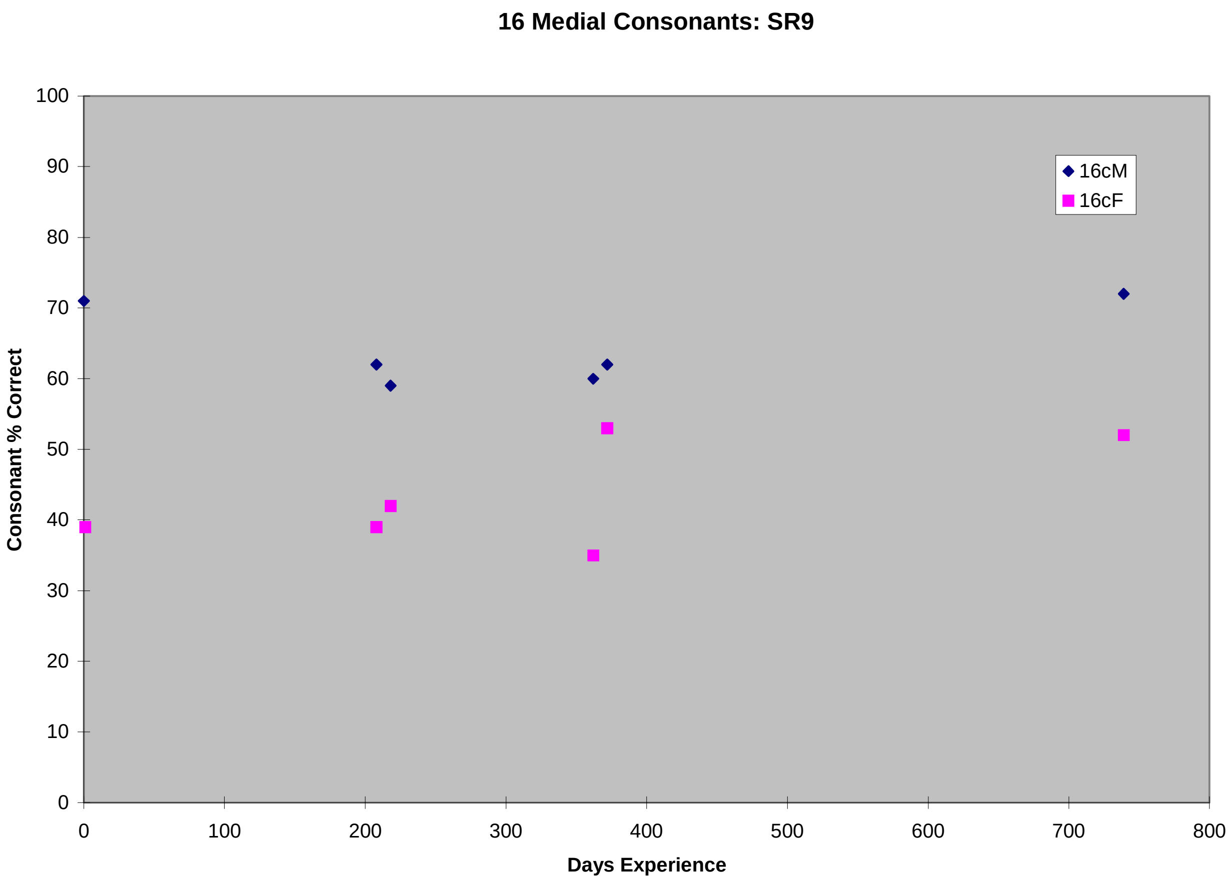

Figure 9. Identification of 16 medial consonants *vs.* length of chronic experience with a CIS processor. Consonant tokens spoken by male and female talkers.

Chronic CIS use continued with processor 9b1 and was next evaluated at about 370 days, when male consonant recognition was found to be unchanged but scores were somewhat lower for the female voice. Retesting with the original five-channel 7b during the same visit demonstrated substantially higher performance with the female voice, and that processor was restored to chronic use.

The most recent measurements with processor 7b, at about 740 days, revealed significant improvements with both male and female consonants. The male consonant identification score was 72±3 %, and that for female consonants 52±3. [Scores for the other four subjects and for SR9's earlier tests may be found in an Appendix to QPR 2.]

The most recent overall information transmission results for processor 7b were 77 % for male consonant identification and 63 % for female.

Monosyllabic word identification tests at about 740 days also demonstrated improvements in performance with extended use of processor 7b. These most recent scores were 16 % for words and 46 % for phonemes.

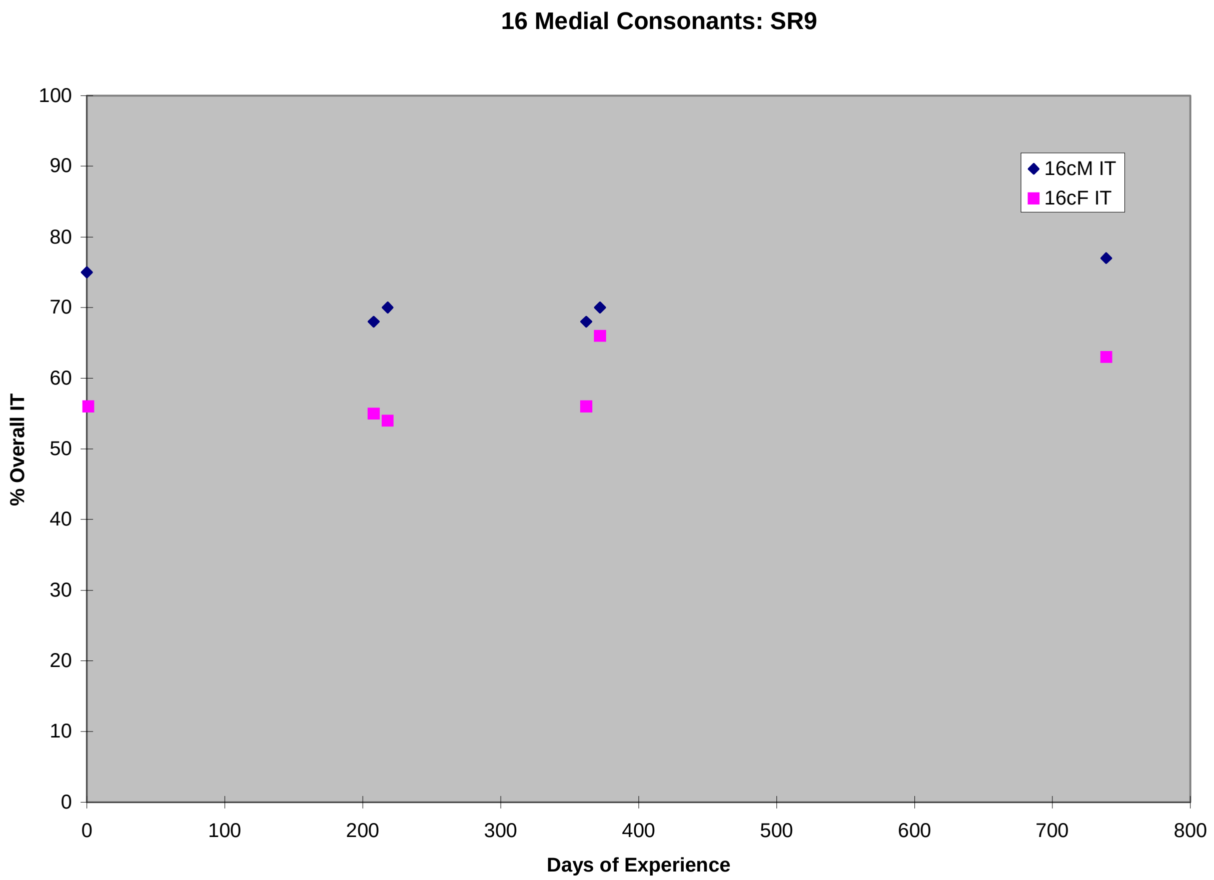

Figure 10. Overall information transmission scores for the same tests represented in Figure A.

Recognition of words in CUNY sentences also was used to compare performance with processor 7b at about 370 and 740 days of experience. The scores, based on four sentence lists including more than 400 words in each condition, were 55 % and 69 %, respectively.

In light of the most recent measurements, our substitution of the six-channel processor 9b1 appears to have constituted an interruption in SR9's considerable progress with experience with the five-channel processor 7b. This qualitatively separates SR9's experience from that of SR15, with whom she was grouped in the summary to our report in QPR 2. A revised summary follows.

Updated Summary

The two subjects with the highest levels of performance in common (SR3 and SR16, with NU6 word scores in excess of 50%) also shared substantial improvements in performance with chronic use experience, including particularly rapid improvement over their first few months with the new processing strategy.

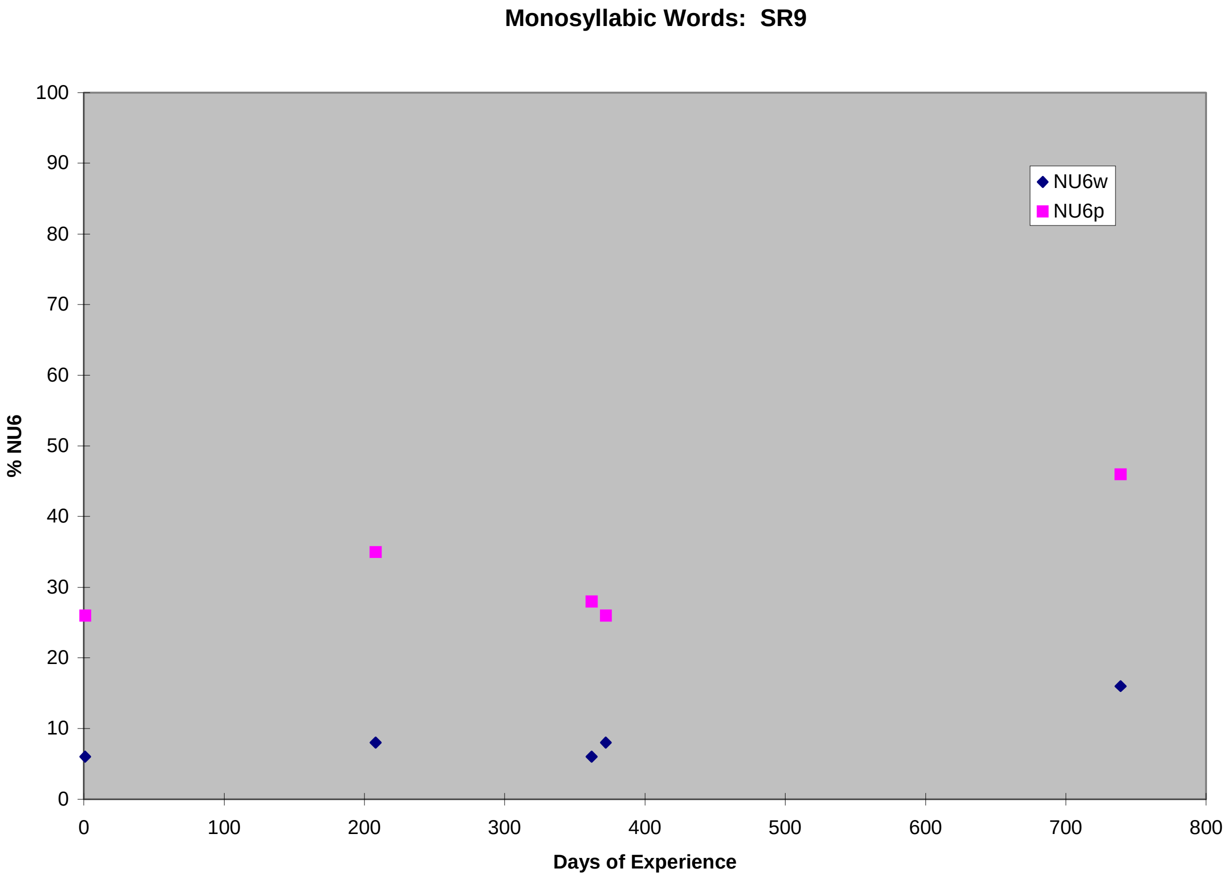

Figure 11. Identification of NU6 monosyllabic words and their constituent phonemes *vs.* length of chronic experience with a CIS processor. Male talker.

Performance by a third subject (SR10) came into the same range after extended experience. All three of these subjects showed substantial improvements over the first year, with two of them continuing to show significant improvements through the second year. Performance improvements for the third subject continued at least through the third year of experience.

Updated data for one of the two subjects with relatively poor levels of performance (SR9) now also show significant sustained improvement with chronic use of a wearable processor. Data for the one subject with the poorest levels of performance (SR15) showed substantial performance differences in laboratory acute studies with various processor designs, but no sustained improvement with chronic use.

IV. Plans for the next quarter

Our plans for the next quarter include the following:

- Ongoing studies with subject SR2. We expect that studies for the next quarter will include completion of work in progress to evaluate effects of manipulations in rate of stimulation and in the cutoff frequency for the lowpass filters in the envelope detectors in CIS processors. We also expect to (a) continue studies in progress to evaluate various implementations of "conditioner pulses" processors and (b) begin evoked potential studies aimed at evaluation of various strategies to replicate noninstantaneous compression functions found in normal hearing.
- Studies with Ineraid subject SR10 during the week beginning on October 25. We expect that the studies will include (a) longitudinal measures with his portable CIS (CIS-Link) processor; (b) extension of prior studies conducted with this subject to evaluate effects of manipulations in rate of stimulation and in the cutoff frequency for the lowpass filters in the envelope detectors in CIS processors, to include additional rates and cutoff frequencies as in recent studies with subjects SR2 and SR9; (c) measures of consonant identification for CIS processors using a wide range of compression functions, also as in recent studies with SR2 and SR9; and (d) measures of intracochlear evoked potentials for single polarities of stimulation using the techniques described in QPR 9 of our prior project.
- Studies with one or two subjects having CI24M implants on both sides (one such subject is provisionally scheduled for the middle two weeks in December). These studies will begin a new series of studies with four or more recipients of CI24M implants on both sides and with as many as ten recipients of COMBI 40+ implants on both sides. The studies with the recipients of the CI24M implants will be conducted in cooperation with the University of Iowa Hospitals and Clinics, and the studies with the recipients of the COMBI 40+ implants will be conducted in cooperation with the Julius-Maximilians-Universität in Würzburg, Germany, the University of Innsbruck in Innsbruck, Austria, and the Med El GmbH in Innsbruck, Austria.
- Continued development of the Access databases mentioned in the Introduction.
- Continued entries into the database for speech processors and associated speech reception studies and initial entries into the databases for psychophysical and evoked potential studies.
- Presentation of project results at the annual *Neural Prosthesis Workshop*, to be held in Bethesda, MD, October 12-14.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

V. Acknowledgments

We thank subjects SR2 and SR9 for their participation in the studies of this quarter . We also would like to thank again bilateral subjects NU-4, ME-2 and NU-5, who participated in studies of prior quarters, as described in section II of this report. We are grateful to Stefan Brill, Joachim Müller, Chris van den Honert and Robert Wolford for their assistance in the studies with one or more of the bilateral subjects.

Appendix 1. Summary of reporting activity for this quarter

Reporting activity for this quarter, covering the period of July 1 through September 30, 1999, included the following:

Finley CC, van den Honert C, Wilson BS, Miller RL, Cartee LA, Smith DW, Niparko JK: Factors contributing to the size, shape, latency, and distribution of intracochlear evoked potentials. Invited lecture presented at the *1999 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 29 through September 3, 1999.

Wilson BS, Zerbi M, Finley CC, Lawson DT, van den Honert C: Relationships among electrophysiological, psychophysical and speech reception measures for implant patients. Invited lecture presented at the *1999 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 29 through September 3, 1999.

Lawson DT, Wilson BS, Zerbi M, Finley CC: Future directions in speech processing for cochlear implants. Invited panel presentation at the *1999 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 29 through September 3, 1999. (Wilson presented the talk for Lawson, who could not attend the conference due to illness.)

van den Honert C, Finley CC, Wilson BS: Measurement of intracochlear evoked potentials. Poster presentation at the *1999 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 29 through September 3, 1999.