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Speech Processors for Auditory Prostheses

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I. Introduction

One of the principal objectives of this project is to design, develop, and evaluate speech processors for implantable auditory prostheses. Ideally, the processors will represent the information content of speech in a way that can be perceived by implant patients. Another principal objective is to develop new test materials for the evaluation of speech processors, given the growing number of cochlear implant subjects enjoying levels of performance too high to be sensitively measured by existing tests.

Work in the present quarter included:

- Continued studies with a local subject (NU4) having standard Nucleus devices implanted on both sides (several half days over the course of the quarter).
- Presentation of project results at the annual *Neural Prosthesis Workshop* in Bethesda , MD (October 16-18).
- Presentation of project results at the *International Workshop on Cochlear Implants*, held in Vienna, Austria, October 24 and 25, where Wilson was designated a guest of honor.
- Completion of speech reception and evoked potential studies with Nucleus percutaneous subject NP5 (weeks beginning September 16 and 23). Nucleus percutaneous subject NP6 was implanted September 25.
- A trip by Zerbi, to discuss loudness mapping procedures with Colette Boex-Spano at MEEI in Boston.
- Continued progress on recordings and control software for new speech tests.

- Continued development of the Evoked Potentials Laboratory.
- Initial evaluation of continuous interleaved sampling (CIS) processors using very high rates of stimulation, in studies with Ineraid subject SR2 (the week beginning October 7).
- Completion of preparations for use of the Geneva/MEEI/RTI portable processor in studies to evaluate possible learning effects with the CIS strategy.
- Discussions with representatives of Cochlear Corporation regarding possible future studies of subjects using new clinical and/or experimental devices.
- Continued analysis of speech reception and evoked potential data from prior studies.
- Continued preparation of manuscripts for publication.

In this report we present results from our studies with bilaterally implanted subject NU4.

Results from other studies and activities indicated above will be presented in future reports.

II. Bilateral Cochlear Implants Controlled by a Single Speech Processor

Among users of cochlear implants, those few patients with functioning devices in both ears represent an especially valuable resource for research. Because of the unique circumstances that led to a second implant in each case, such patients present a wide variety of potential experimental opportunities and limitations. In some cases quite different devices were implanted on the two sides, allowing comparisons between those devices in the same subject. Additional research opportunities are available in patients with identical devices implanted bilaterally, although a fully equivalent situation on the two sides is unlikely given the circumstances that typically have led to a second, contralateral surgery.

Subject

We here report some initial studies with a local subject, NU4, who has bilateral Nucleus 22 implants. Having been rendered profoundly deaf by Listeria rhomboencephalitis as a young adult, she received a cochlear implant on the right side in May of 1991. Obstruction of scala tympani limited that insertion to 18 of the 22 active electrodes and, when radiographic studies revealed rapidly progressing ossification bilaterally, a decision was made to proceed at once with implantation of an identical device on the other side. That surgery took place in October of 1991 and achieved a full insertion. Both operations were performed at Duke University Medical Center by surgeon John T. McElveen, Jr.

NU4 now routinely uses a pair of independent clinical MSP processors with her two implants. She was referred to us for studies by DUMC audiologist Patricia Roush and otologic surgeon Joseph C. Farmer, Jr. NU4 has participated in a total of 12 half-day sessions thus far, about half of which were in September and October 1995 and the other half in August and September 1996. The birth of the subject's second child caused the pause in our studies.

From the very long list of studies we would like to undertake with this subject, we have begun a few. (1) All usable BP+1 electrode assignments on both sides have been included in common studies of pitch discrimination and pitch ranking. Among our initial questions in these studies were the total number of perceptually distinct channels available, whether any bilateral pairs of electrodes were closely matched perceptually, and the nature of any perceptual differences between contralateral and ipsilateral comparisons. (2) Based on these initial results, we have begun studies of the subject's ability to detect and utilize interaural delays and interaural amplitude differences. (3) Laboratory studies have been undertaken to assess potential benefits of placing stimulation of the electrodes in both ears under the control of a single continuous interleaved sampling (CIS) processor. Among the potential benefits for such a processor with a single microphone input are the ability to double the effective stimulation rate limit imposed by the Nucleus transcutaneous link for a given number of CIS channels, the possibility of reducing the effects of channel interactions, and access to additional or alternative independent channels of stimulation. With input microphones at both ears, the potential benefits of such a processor include the ability to convey direction of sound incidence and improved performance in noisy acoustic environments.

Apparatus

Laboratory hardware and software of our own design transmitted instructions and power to the subject's implanted receiver/stimulators. Essentially, this was done by providing the signals identified as DAMP and OUTPUT in Figure 21 of U. S. Patent 4,532,930 for the Nucleus prosthesis. [Appendix 2 of our QPR2 for NIH project N01-DC-9-2401, the quarter ending October 31, 1989, described an earlier version of such an interface, using different hardware.] Speech processor strategies and psychophysical testing routines were executed in real time by the same digital signal processor (DSP) used for a variety of other studies in our laboratory. The interface hardware specific to Nucleus transcutaneous studies relieves that DSP of the additional task of timing and counting the pulses in each command burst sent to the implanted circuits. The interface appears to the DSP as two separate memory spaces, one for each ear, which are loaded with the appropriate counts to generate the next control word bursts to each side. Within the interface, counters are loaded with those numbers and then decremented as the output pulses are generated. When a counter reaches zero the interface generates an interrupt to the DSP, indicating readiness for the next burst count for that ear, and automatically begins to count down the minimum inter-burst interval. At the end of that interval the interface will initiate a new burst if a new count has been loaded. The DSP controls stimulation pulse rate by timing the loading of the first burst for each new pulse's command sequence.

Comparisons among electrodes

We began by considering all the BP+1 electrode pairs that had been used in the subject's prior clinical fittings. Contrary to our normal practice, in this report we shall follow the convention used clinically for the Nucleus 22 device and refer to the electrodes by numbers beginning at the *basal* end of the array. Each BP+1 pair of electrodes will be referred to by the number of its *more basal* member, *i.e.* "electrode 20" will refer to the bipolar pair including the apicalmost and third apicalmost of the 22 active bands in a Nucleus implanted array. Finally, each electrode label will carry a prefix to indicate the ear in which it is implanted. In these terms, then, we began by considering use of electrodes R10 through R20 in the subject's right ear and L2 through L20 in the left.

In the course of our measurements of pulse amplitudes corresponding to threshold and comfortably loud percepts (the subject was instructed to report the same "T" and "C" levels that had formed the basis for her clinical fittings), we decided not to utilize certain electrode combinations: L2, L3, L13, R10, R11, and R12 were eliminated because of somatic percepts at some or all of the pulse rates and pulse durations tested. The remaining 16 electrodes on the left and 8 on the right were included in formal studies of pitch discrimination and ranking.

Table I indicates the pulse amplitudes (in clinical units) corresponding to threshold (T level) and comfortably loud (C level) percepts for 50 ms bursts of 80 us/phase pulses at 400 pps for these 24 electrode locations. All of these C levels were carefully loudness balanced across electrode locations on both sides.

Table I. T and C levels, 80us/phase, 400pps, 50ms bursts.

Electrode	T level	C level	Electrode	T level	C level
L4	158	213	R13	142	207
L5	148	196	R14	140	208
L6	147	193	R15	141	206
L7	140	188	R16	137	199
L8	151	204	R17	139	202
L9	147	207	R18	141	208
L10	149	212	R19	146	205
L11	145	216	R20	138	202
L12	142	221			
L14	142	219			
L15	136	210			
L16	128	194			

L17	129	197
L18	139	207
L19	142	206
L20	134	192

The procedure used for our initial studies of pitch discrimination and ranking was one developed to rapidly identify the maximum number of perceptually distinct stimulation sites for each subject in our 22 electrode percutaneous study [QPRs 1 and 3, current project]. A pair of 50 ms stimuli separated by 500 ms (400 pps bursts of 80 us/phase pulses loudness balanced at C level amplitudes) were delivered to two different electrode sites. The subject was asked to indicate whether the second sound was higher or lower in pitch (two alternative forced choice). Initially, each comparison was for electrodes separated by a fixed, relatively large distance, specified by an initial offset D in electrode number. After a specified number of randomized comparisons of each pair of electrodes sharing that separation (n presentations of each pair in each order) D was reduced by one and the process repeated. Thus a subject typically would experience clear pitch contrasts early in the test, gradually becoming more subtle until D = 1 had been explored, or until responses for every pair of electrodes was at chance level for some larger value of D. The percentage of responses consistent with normal tonotopic order along the cochlea could then be displayed in a matrix of absolute electrode position *vs.* electrode separation D, forming a map of pitch discrimination across the electrode array against which various proposed subsets of electrodes could be considered for assignment to CIS speech processor channels. For this bilateral subject we began with a study pitch ranking the sixteen left ear electrode sites (L4 - L12 and L14 - L20). We then compared the pitch associated with stimulation of R20, determining that L11 stimulation produced slightly higher, L12 identical, and L14 lower pitch percepts than R20. Finally, a bilateral combined total of 17 electrode sites (L4 - L12 and R13 - R20) were included in a study to assess pitch ranking over the common range accessible to both implants. In base to apex order on each side, stimulation locations from the two sides appeared alternately in the arbitrary list that served as a starting point for this bilateral study.

Results of these pitch ranking studies are summarized in Tables II and III and Fig. 1. In the nomenclature of these results a "consistent" response is one indicating that pitch ranking is consistent with the order of the list being evaluated.

Table II. Pitch Ranking among LE Electrodes

More basal of compared locations	D=1: % consistent	D=2: % consistent	D=3: % consistent	D=4: % consistent	D=5: % consistent
L4	40	60	50	75	100
L5	40	70	100	75	100
L6	40	90	100	100	100
L7	70	90	100	100	100
L8	80	100	100	100	100
L9	100	100	100	100	100
L10	90	100	100	100	100
L11	100	100	75	100	75
L12	90	100	100	100	100
L14	100	90	75	100	100
L15	90	90	100	100	100
L16	90	100	75	100	
L17	90	100	100		
L18	100	100			

L19	100				
L20					
Overall % consistent	81%	92%	90%	96%	98%
Number of times each comparison presented	10	10	4	4	4

When the left ear is considered alone, as in Table II, we see that the stimulation of any adjacent (D = 1) locations from L8 through L20 (excluding L13 as noted above) can be discriminated on the basis of pitch ranking, and that L4, L5, or L6 can provide one additional discriminable site. The pitch ranking is consistent with normal tonotopic ordering within the cochlea.

Table III. Bilateral Pitch Ranking, Common Pitch Region

First of compared locations in list order	D=1: % consistent	D=2: % consistent	D=3: % consistent	D=4: % consistent	D=5: % consistent
L4	50	50	50	50	100
R13	21	50	25	75	25
L5	79	50	75	75	100
R14	43	100	50	100	75
L6	86	50	100	100	100
R15	14	75	25	100	50
L7	93	100	100	100	100
R16	7	100	25	100	75
L8	100	100	100	100	100
R17	14	75	100	100	100
L9	100	100	100	100	100
R18	43	100	100	100	100
L10	96	100	75	100	
R19	50	75	100		
L11	93	100			
R20	43				
L12					
Overall % consistent	87---29	81---82	85---61	89---96	100---71
Nature of comparisons	bilateral	unilateral (D = 1)	bilateral	unilateral (D = 2)	bilateral
Number of times each comparison	14	4	4	4	4

presented					

We identified three bilateral pairs of electrode sites as capable of supporting interaural comparisons with no perceptible difference in pitch: L12 formed such a pair with R20, L11 with R19, and L10 with R18. The signature for such a pair can be found in the D = 1 column of Table III where firmly ranked bilateral pairs (e.g. in the rows labeled L9, L10, and L11) alternate with indiscriminable bilateral pairs (e.g. in the R18, R19, and R20 rows).

It is important to note, when examining the D = 1 column of Table III, that "% consistent" scores significantly *below* 50 denote discrimination and ranking in a pitch order *counter* to that of the arbitrary bilateral list. Notice also that columns labeled at the top with odd values of D correspond to bilateral comparisons, whereas D = 2 and D = 4 in fact amount to D = 1 and D = 2 *unilateral* comparisons, respectively. Finally, note that comparisons of the two "overall % consistent" entries near the bottom of each column indicate roughly equivalent performance on the two sides for unilateral comparisons and a strong asymmetry only for D = 1, where pitch ranking exceptions to the arbitrary list order were to be expected.

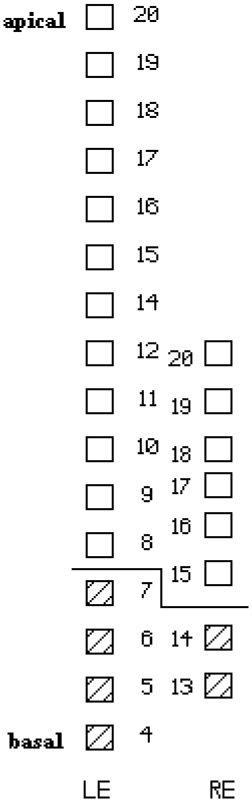
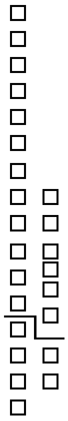


Figure 1. Schematic representation of relative pitch, bilateral implants.

Fig. 1 indicates schematically the relative pitch percepts associated with all 24 sites of stimulation. Along with L4 through L7, which have already been discussed, the symbols for R13 and R14 are set off from the others by a line and shaded to indicate the unavailability of reliable pitch ranking near the basal end of each set of usable electrodes. As noted above, R20, R19, and R18 are shown with pitches identical to L12, L11, and L10 respectively. Based on the results from Table III, R17 has been placed between L9 and L10 in pitch (14% consistent with the list order between R17 and L9 means 86% consistent with the opposite order). Based on anecdotal comments, R17 has been placed closer to L9 in pitch. Similarly, R16 is shown as having a pitch intermediate to those associated with stimulation of L8 and L9 (93% consistent with this exception to the list order), and R15 as having a pitch between those of L7 and L8 (86% consistent with the altered order). As may be seen from this diagram, we have identified a total of 16 stimulation sites that are discriminable and can be ranked reliably on the basis of pitch – assuming use of only one member from each of the three pairs of sites sharing identical pitch percepts, and use of only one site from the following group: L4, L5, L6, R13, and R14.



The pattern of Fig. 1 will be used as shown above later in this report, as a convenient way of indicating relative pitch percepts and bilateral distributions for the various subsets of stimulated electrodes used in subsequent studies. The boxes corresponding to stimulated sites will be filled in each case, with numbers alongside them indicating the processor channel number (in our normal order of *ascending* frequency bands) where appropriate.

Interaural delay studies

Our initial studies of this subject's ability to make use of interaural delay information also have been based on a two alternative forced choice task, one in which the subject is presented with bilateral stimuli and asked whether the sound seemed to come more from the left or more from the right side. Responses are scored as correct when the identified side is the one receiving the earlier stimulation, so 100% corresponds to perfect discrimination and identification of the side receiving the earlier stimulus, and absence of discrimination will result in random responses and a score close to 50%. The stimuli are pitch matched and loudness balanced at C level: 50 ms bursts of 80 us/phase pulses at 480 pps, with controlled interaural delays. The program constructing an individual testing session is supplied with a list of the interaural delay times to be investigated, in order of decreasing delay, and a specification of the number of four-stimulus groups to present at each delay setting. Every such set of four stimuli includes two for each sign of the interaural delay, with the order of presentation randomized within each set. This ensures that there will be no more than four presentations in a row with interaural delays of the same sign (two from one set and two from the following set). Thus each test begins with relatively large interaural delays and proceeds gradually to smaller and smaller values. Such studies have been conducted with each of the subject's three same-pitch pairs of electrodes.

Our very first measurements were for the L10,R18 pair, with a coarsely spaced set of interaural delays ranging from 500 down to 30 us. All scores were 100% for delays at and above 300 us, so for all subsequent tests we adopted a set of interaural delay values extending downward from 325 us in 25 us intervals [the smallest was 30 us rather than 25 us, because of a limitation in the testing apparatus]. Our goal was to trace out the transition, as a function of decreasing interaural delay, from 100% scores to chance levels of performance for each of the three pitch-matched bilateral pairs of stimulation sites. In the course of several sessions spread out over a month, there were indications of differences in the shape of this transition among the sites, and of a tendency for overall performance to decline somewhat after prolonged testing. Pending further studies and statistical analysis, in Fig. 2 we show the summed data for each condition, comprising a total of 80 presentations at each delay for the L10,R18 pair, 120 for L11,R19, and 60 for L12,R20.

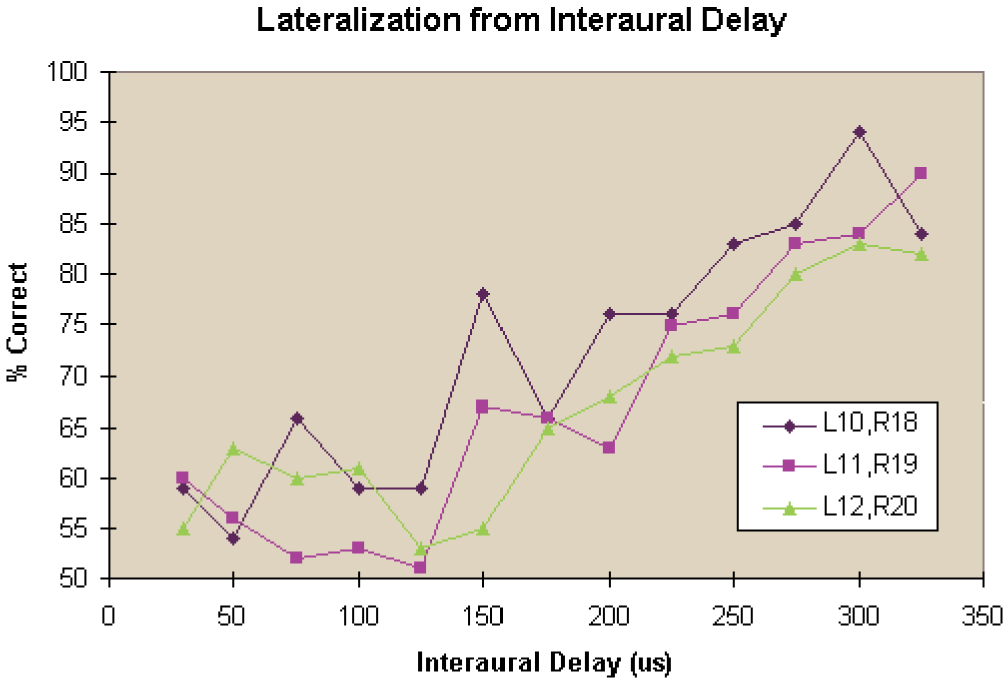


Figure 2. Lateralization from Interaural Delay

Taking advantage of a brief opportunity during a recent session with the subject, we obtained contemporaneous results from 80 additional presentations to each of the three matched pairs of sites for two specific values of interaural delay – 150 and 200 us. The results were as follows:

	150 us	200 us
L10,R18	80%	81%
L11,R19	61%	75%
L12,R20	76%	86%

While further studies and analysis are needed to characterize fully this transitional range of delay values, we have demonstrated this subject's ability to identify the ear receiving the earlier onset for interaural delays at least as short as 150 us. For a 9 cm head radius, a 150 us difference in arrival time at the two ears corresponds to incidence from only about 15 degrees to one side. This represents a much greater sensitivity than that reported by van Hoesel *et al.* for studies with two other bilateral implant subjects [RJM van Hoesel, YC Tong, RD Hollow, and GM Clark, *J. Acoust. Soc. Am.* **94**, 3178-3189 (1993).]

Interaural amplitude difference studies

Studies of the subject's ability to utilize interaural amplitude differences have also begun, based on another two alternative forced choice task essentially like the one described above for interaural delay studies. In this case a list of pulse amplitudes (in clinical units) is supplied for the chosen pitch-matched electrodes on each side, beginning with loudness balanced C-level reference amplitudes. Also specified is the number of randomized-order four-stimulus sets to be presented, pairing the reference amplitudes with each successive pair of reduced levels contralaterally. Each stimulus includes a reference level signal to one side and a reduced signal to the other. Initially the reduced signals correspond to the minimum amplitudes of the list, producing the largest amplitude difference cues. As the testing session proceeds, the reduced signals use successively larger amplitudes from the list, making the interaural differences progressively smaller.

An initial coarse set of amplitudes for each of the three pitch-matched pairs of stimulation sites revealed 100% accuracy in identifying the ear receiving the larger, reference amplitude whenever the amplitude differences were 11 clinical units (cu) or more. Thereafter, the amplitude lists for L10,R18 and L11,R19 were constructed to cover amplitude differences of from one to ten cu at intervals of 1 cu. Similarly, the list for L12,R20 covered differences of from two to 20 cu in steps of 2 cu. Preliminary results for eight presentations in each condition are shown in Fig. 3.

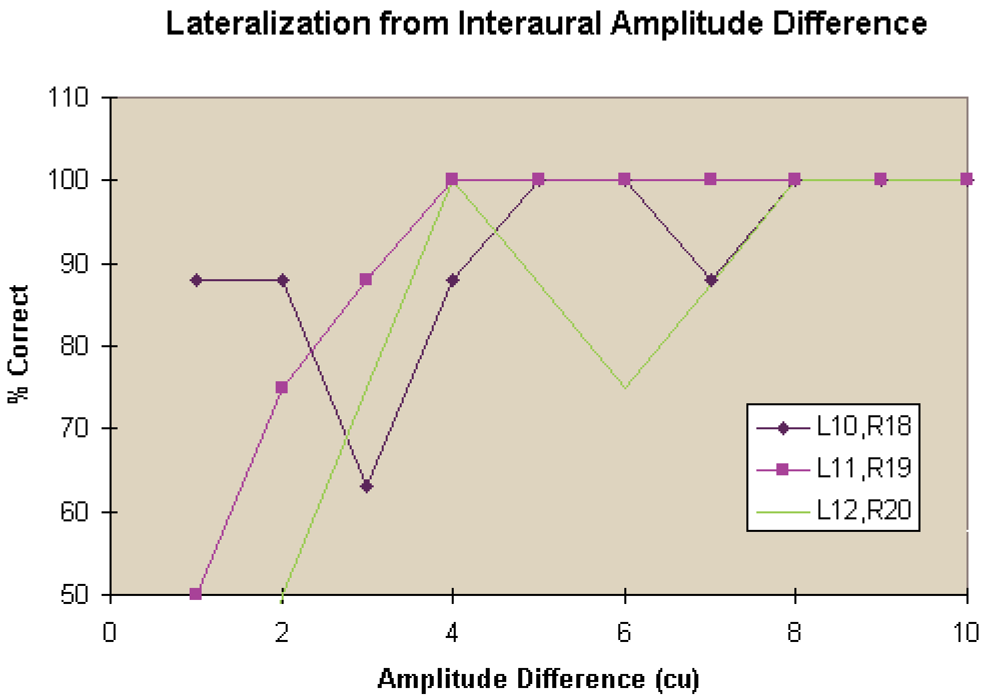


Figure 3. Lateralization from Interaural Amplitude Difference

The subject is able reliably to lateralize a C-level sound percept on the basis of a 1 cu difference in pulse amplitude at L10,R18; on the basis of a 2 cu difference at L11,R19; and on the basis of a 4 cu difference at L12,R20. Based on calibration data from the manufacturer of the implanted devices, Table V below indicates the corresponding current amplitude differences and approximate absolute amplitudes, the amplitude differences in decibels, and the overall dynamic ranges for each of the same-pitch pairs of electrode sites.

Electrodes	amplitude difference (cu)	amplitude difference (ua)	absolute amplitude (ma)	amplitude difference (dB)	dynamic range (dB)
L10,R18	1	16	1.1	0.125	9.5
L11,R19	2	31	4.4	0.24	8.7
l12,R20	4	55	1.2	0.39	9.5

At least in the case of L10,R18, this subject is capable of identifying reliably the ear receiving the louder stimulus for the smallest differences in pulse amplitude available from her implanted receiver/stimulator – a difference that corresponds to only about 1/75 of her overall dynamic range for electrical stimulation.

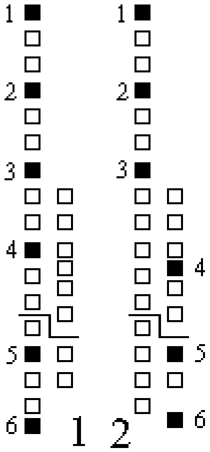
Speech processor comparisons

With this subject, we have used medial consonant identification tests (10 presentations of each of 16 consonant sounds in /a/ C /a/ context recorded by a male talker and presented without visual cues or feedback) to compare a number of different speech processors. For each comparison, results of the medial consonant tests will be presented in the form [percent correct ± standard deviation of the mean: percent overall information transmission]. As a point of reference, the subject's scores with her left ear clinical MSP processor alone were [74±5: 83] and for simultaneous use of clinical MSP processors bilaterally [74±5: 81].

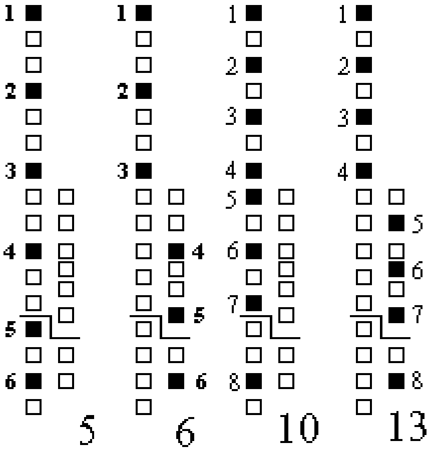
The initial continuous interleaved sampling (CIS) speech processor configurations studied with this subject were chosen to help answer several immediate and fundamental questions. These questions included (1) whether bilateral stimulation might be distracting to the subject or otherwise generally reduce the performance of speech processors *vis a vis* equivalent unilateral designs; (2) whether an additional contralateral channel might be equivalent to an additional ipsilateral channel in terms of speech processor performance; and (3) whether the availability of bilateral electrodes under the control of a single speech processor might support higher speech reception scores through such factors as the availability of additional channels, the possibility of reducing channel interactions for a given number of channels, and the ability to increase the effective CIS stimulation rate on each channel. We shall present examples of results that address each of these questions. Appendix I provides full parametric specifications for each of the CIS processors discussed in the text.

While we have chosen to discuss them last in this report, comparisons of new speech processor designs were distributed throughout out twelve half-day sessions with NU4.

Search for Possible Negative Impact



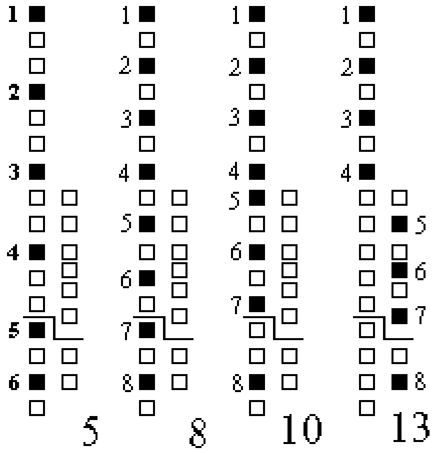
One of our earliest concerns was whether bilateral stimulation might be distracting to the subject or otherwise destructive of speech processor performance. Processors 1 and 2 were the first designed to explore this possibility. Both were six channel CIS processors with 520 pps stimulation rates on each channel, and both included electrodes spanning the full tonotopic range of the full insertion side. All electrodes for processor 1 were from the left side, while the basalmost three were replaced by roughly equivalent right ear locations in processor 2. Anecdotally, the subject was well aware of the bilateral nature of processor 2 but did not find it distracting or note the decrease of information on the left side. Consonant identification test scores were [82±3: 86] for the unilateral left ear (LE) processor 1 and [78±3: 83] for the bilateral (BE) processor 2. While there was a difference, it was a reassuringly small one.



Each of the above processors included one electrode (L3 in processor 1 and R10 in processor 2) that was eventually eliminated from use because of somatic percepts in some circumstances. Subsequent comparisons addressing the same potential concerns included processors 5 *vs.* 6 – six channel 480 pps processors; LE *vs.* BE, [77±3: 85] *vs.* [75±4: 83] –

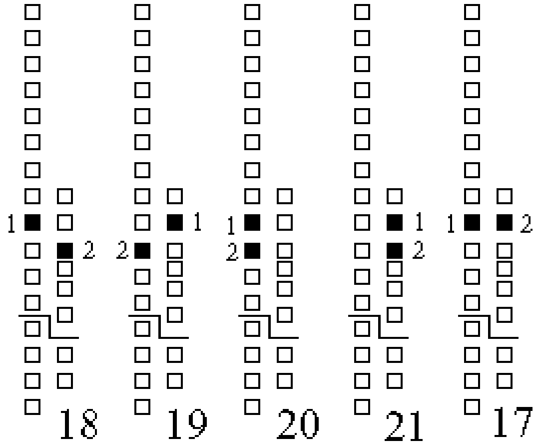
and processors 10 *vs.* 13 – eight channel 480 pps designs; LE *vs.* BE, [89±2: 90] *vs.* [86±2: 89]. While the basalmost pair of sites used by processor 5 were subsequently found to be poorly discriminated in pitch ranking studies, processors 10 and 13 included only clearly discriminable sites of stimulation. **We have found no evidence that bilateral stimulation *per se* damages speech processor performance, even when information from opposite halves of the analyzed spectrum is directed to the two ears.**

Equivalence of Additional Ipsilateral and Contralateral Stimulus Sites



While we have not yet compared the addition of a single ipsilateral channel to the addition of a single contralateral channel with respect to a common reference processor, three of the four processors just mentioned provide relevant comparisons for the addition of two channels in each case.

If we take the six channel LE processor 5 [77±3: 85] as our reference, we can compare various ways of adding two more channels. Processor 8 [84±3: 87] added them ipsilaterally. As already noted for processor 5, the basalmost pair of stimulation sites in processor 8 were subsequently found to be poorly discriminated in pitch ranking studies. Processor 10 [86±2: 89] provided an ipsilateral alternative without that potential defect. These results may be compared with those for processor 13 [89±2: 90] in which the basal half of the eight channels were provided contralaterally. **Additional contralateral as well as ipsilateral channels can improve speech processor performance. The effects of the two options can be equivalent.**

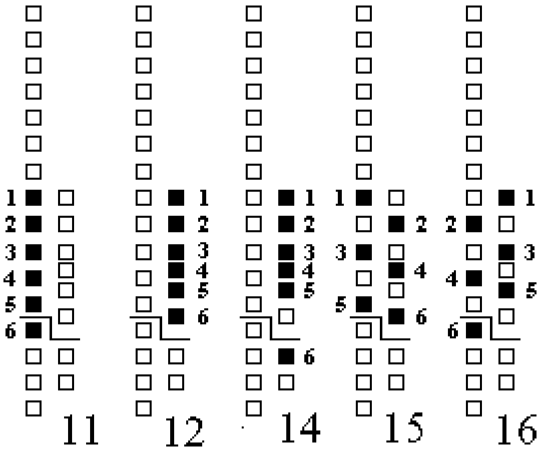


We also have completed consonant tests with the first pair of a series of two- channel processors designed to explore issues of channel equivalence with respect to differences in side of stimulation and differences in the pitch associated with each stimulation site. The overall series, as indicated in the diagrams, utilizes two of the subject's pitch-matched pairs of bilateral stimulation sites to support processors whose two channels address stimulation sites that differ in pitch alone (same ear), ear alone (same pitch percepts), or both. This first comparison – between processors 18 and 19 – was a member of the last of these categories and revealed a significant difference in performance depending on which ear received the lower frequency and which the higher frequency channel, despite the channels' being associated with the same pitch percepts in each case. The consonant identification scores were [70±3: 80] for processor 18 (L11 as channel

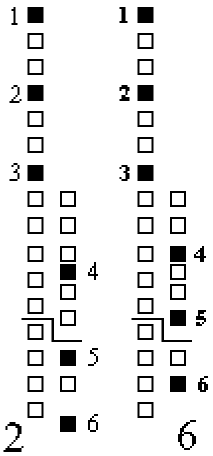
1 and R18 as channel 2) and [58±3: 76] for processor 19 (R19 as channel 1 and L10 as channel 2).

Potential Benefits of Bilateral Stimulation

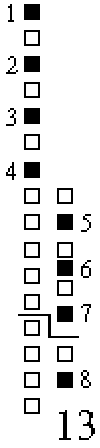
Reduction in channel interactions for a given number of channels. We already have discussed several comparisons of 6 channel and 8 channel processors using stimulation sites spanning the whole pitch range available to the fully inserted electrode array. The fact that the sites on one side span only about the basal half of that range does limit the potential for reducing channel interactions by making use of bilateral design options. A staggered order of stimulation, for instance, provides the same intervals between stimulation of adjacent active sites in unilateral processor 5 as in bilateral processor 6. There may still be some advantage in halving the aggregate stimulation rate in each ear, however.



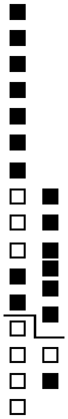
Another series of processor comparisons has been carried out with the use of only those stimulation sites that are associated with pitch percepts within the range common to both sides – L4 through L12 and R13 through R20. All processors in this series have stimulation rates of 480 pps on each of six CIS channels. Three of the processors are unilateral – processor 11 [70±4: 77] on the left side, and processors 12 [57±5: 70] and 14 [76±3: 82] whose sites span slightly narrower and slightly wider ranges, respectively, on the right side. Further studies are needed to learn more about the source(s) of such a dramatic difference between the latter two. The remaining processors of this series are bilateral, with the channels for successive frequency bands assigned to electrodes on alternating sides. Bilateral processors 15 [79±3: 88] and 16 [82±2: 90] achieve quite similar consonant identification scores; both significantly better than any of the unilateral designs restricted to a comparable range.



Increase in effective stimulation rate for a given number of channels. For any CIS speech processor in which the number of stimulation sites is fairly evenly divided bilaterally, a substantial increase in the rate of stimulation on each channel can be realized simply by allowing simultaneous stimulation of sites on both sides. All pulses within each ear remain non-simultaneous. One such comparison was included early in our work with subject NU4. Some early tests with six channel designs compared 520 pps processor 2 [78±3: 83] with 980 pps processor 3 [81±2: 85]. In the latter case, channels 1 and 4 were stimulated simultaneously, as were channels 2 and 5 and channels 3 and 6. These early processors included one stimulation site (R10) later found to produce somatic percepts in some circumstances. A similar six-channel comparison between a 480 pps processor 6 [75±4: 83] and a 700 pps processor 7 [74±3: 81] used sites that all met our pitch ranking criteria, but in that case the increased stimulation rate was accomplished without simultaneous bilateral stimulation. In both of these cases substantial rate increases produced little or no change in overall performance.



A third comparison involved CIS processors with eight channels: a 480 pps processor 13 [89±2: 90] and a 700 pps processor 9 [76±5: 83]. In this case, the slower processor supported superior consonant recognition. This result might be seen as consistent with recent modeling and intracochlear EP studies indicating relatively simple relationships between pulse amplitude envelopes and the resulting neural activity for rates up to a few hundred pps and again for rates of at least several thousand pps. In those studies, intermediate pulse rates tend to result in much more complex and variable representations. The lack of any similar sensitivity to rate in either of the two six-channel comparisons, however, argues for some other explanation.



Additional channels. We already have discussed improvements in processor performance observed for increases from six to eight channels in both unilateral and bilateral contexts. As also noted earlier, this subject has as many as 16 stimulation sites bilaterally that can be ranked accurately by pitch. As may be seen in Fig. 1, the assignment of channels to those sites could be divided almost evenly between the two ears (seven on the right -- including members of all three pitch-matched pairs and R13 or R14 -- and the remaining nine on the left). Thus a 16 channel CIS processor could be constructed for this subject with an effective rate about the same as for a nine channel unilateral design. Future studies will include exploration of performance trade-offs between stimulation rate and number of CIS channels for this subject and her implanted hardware.

Plans for continuing laboratory studies

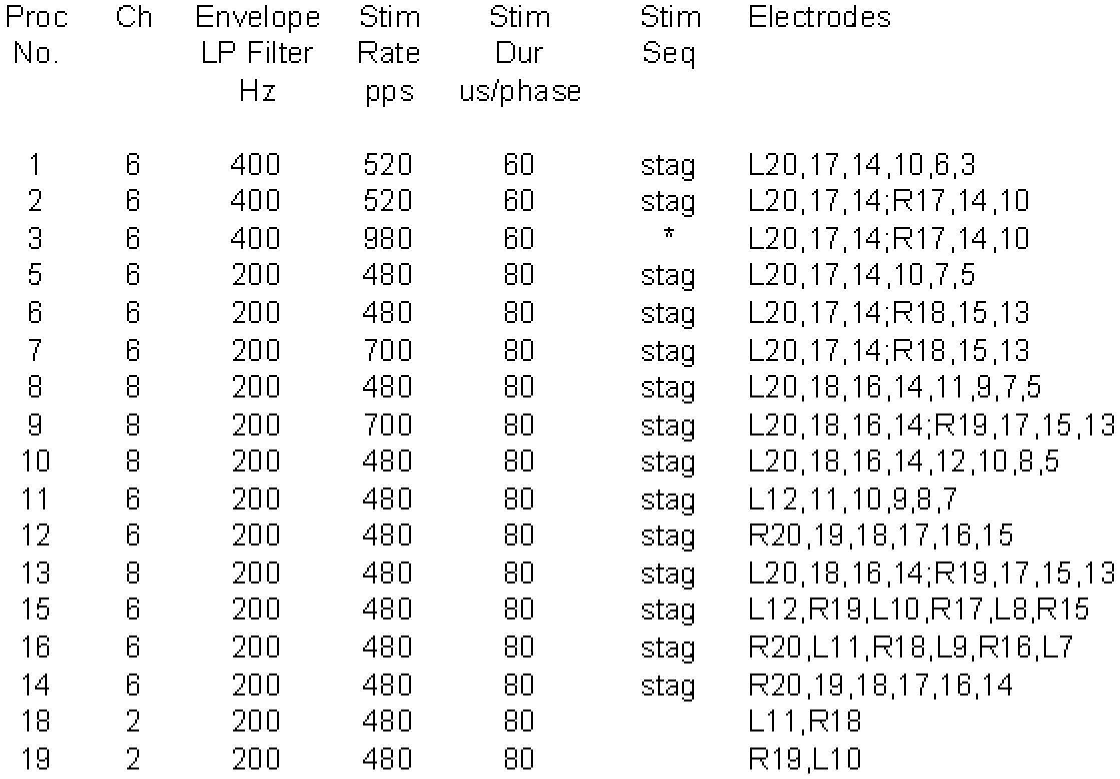
In addition to continuing the studies outlined above, we plan in the near future to conduct laboratory studies of speech processors that control stimulation of the electrodes on both sides in ways specifically designed to utilize this subject's ability to resolve interaural delays. Controlled speech reception tests in which different interaural delays will be provided for speech and for competing noise are being planned, as well as acute free field tests of single processors with separate left and right ear microphone inputs.

Plans for chronic use studies

While we see no way to exploit this subject's interaural delay sensitivity with available independent clinical processors, we plan to try to maximize her ability to use her interaural amplitude difference sensitivity with such hardware, specifically a pair of SPECTRA units running bilateral SPEAK processing strategies with the partial insertion side's electrodes assigned to the same spectral regions as contralateral electrodes sharing the same pitch percepts. This would ensure that amplitude difference information for common spectral regions would reach common areas of the brainstem.

Appendix I.

Parameters of CIS Processors Mentioned in the Text



Proc No.	Ch	Envelope LP Filter Hz	Stim Rate pps	Stim Dur us/phase	Stim Seq	Electrodes
1	6	400	520	60	stag	L20,17,14,10,6,3
2	6	400	520	60	stag	L20,17,14;R17,14,10
3	6	400	980	60	*	L20,17,14;R17,14,10
5	6	200	480	80	stag	L20,17,14,10,7,5
6	6	200	480	80	stag	L20,17,14;R18,15,13
7	6	200	700	80	stag	L20,17,14;R18,15,13
8	8	200	480	80	stag	L20,18,16,14,11,9,7,5
9	8	200	700	80	stag	L20,18,16,14;R19,17,15,13
10	8	200	480	80	stag	L20,18,16,14,12,10,8,5
11	6	200	480	80	stag	L12,11,10,9,8,7
12	6	200	480	80	stag	R20,19,18,17,16,15
13	8	200	480	80	stag	L20,18,16,14;R19,17,15,13
15	6	200	480	80	stag	L12,R19,L10,R17,L8,R15
16	6	200	480	80	stag	R20,L11,R18,L9,R16,L7
14	6	200	480	80	stag	R20,19,18,17,16,14
18	2	200	480	80		L11,R18
19	2	200	480	80		R19,L10

[All these processors used 6th order bandpass filters with logarithmically equal width filters spanning an overall range of 350 to 5500 Hz. All used a standard preemphasis filter, fullwave rectification, 2nd order envelope smoothing filters, and the same standard mapping law.]

* Stimulation in simultaneous bilateral pairs; see discussion in text.

III. Plans for the Next Quarter

- Initial studies with Ineraid subject SR16, scheduled for the week beginning November 11, 1996.
- Additional studies with Ineraid subject SR14, previously studied by us in 1994. Aaron Parkins of the University of Iowa, where SR14 recently received a COMBI-40 processor, will accompany the subject and participate in the

studies.
- Analysis of the results of open set speech tests for the first five subjects (NP1-NP5) of our 22 electrode percutaneous series.
- Forward masking studies to infer spatial patterns of excitation with the Ineraid implanted array and various type of stimuli.
- Studies of evoked potentials in response to pairs of stimulus pulses.
- Continued analysis of speech reception and evoked potential data from prior studies.
- Continued preparation of manuscripts for publication.

IV. Acknowledgments

We thank subject NU4 for her participation in the studies described in this report, and subjects NP5 and SR2 for their participation in other studies conducted this quarter.

Appendix A. Summary of Reporting Activity for this Quarter

Reporting activity for the last quarter, covering the period from May 1 to October 31, 1996, included the following presentations:

Wilson, BS, Lawson, DT: Speech processors for auditory prostheses. Invited lecture, *Twenty-seventh Neural Prosthesis Workshop*, Bethesda, MD, October 16-18, 1996.

Wilson, BS: High-rate coding strategies. Invited lecture, *International Workshop on Cochlear Implants*, Vienna, Austria, October 24-25, 1996.