First 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 of 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 and/or temporal patterns of neural activity.

Work in this first quarter included:

- Studies with Ineraid subject SR10, from September 28 through October 9. The studies included (a) measures of forward masking across electrode positions, using the procedure of Lim *et al.*, to map excitation patterns for maskers at each of the six electrodes in the Ineraid implant; (b) longitudinal measures of speech reception performance with chronic use of a portable CIS processor; (c) measures of electrode interactions using recordings of intracochlear evoked potentials; (d) measures of consonant identification and sentence recognition for 15 conditions combining different rates of stimulation and cutoff frequency of the lowpass filters in the envelope detectors for CIS processors; (e) psychophysical scaling of pulse rate for unmodulated pulse trains, for each of the six electrodes; (f) psychophysical scaling of modulation frequencies for SAM pulse trains, for one of the electrodes and various depths of modulation; (g) psychophysical scaling of electrodes, for unmodulated pulse trains delivered to each of the electrodes and for SAM pulse trains delivered to each of the electrodes; (h) measures of forward masking across electrode positions, but now using recordings of intracochlear evoked potentials instead of the psychophysical procedure above; (i) recordings of the electrically evoked auditory brainstem response, using some of the same stimuli used for this subject in prior recordings of intracochlear evoked potentials; (j) evaluation of processors suggested by results of various psychophysical scaling studies above, *e.g.*, evaluation of processors using fewer than 6 channels to increase perceptual differences among channels; (k) comparisons of CIS processors using different update orders in each cycle of stimulation across electrodes; and (l) a comparison between 3-channel CIS processors, each with a cycle rate of 500/s, but with one presenting pulses at the beginning of each cycle with no time delay between pulses, and the other presenting pulses spaced evenly in time across the cycle. The scaling experiments extended greatly the range of conditions included in initial studies with this and other subjects, as reported in QPR 8 for the prior project in this series (NIH project N01-DC-5-2103).

- Studies with Ineraid subject SR15, from November 18 through November 21. The studies included some of those conducted for SR10 above, including studies (a), (b), and (e). Additional scaling studies included scaling of modulation frequencies for SAM pulse trains and 3 electrodes, for various depths of modulation, and scaling of modulation frequencies for all electrodes with 100 percent modulation. Studies with SR15 also included evaluation of various 2, 3 and 4 channel CIS processors, as suggested by results from the psychophysical scaling experiments and other considerations.

- Ongoing studies with Ineraid subject SR2, seven half days during the present reporting period. The studies included forward masking and psychophysical scaling studies like those conducted with subjects SR10 and SR15 above; initial evaluation of "conditioner pulses" processors (see Rubinstein *et al.*, 1998, and the Final Report for the prior project in this series); measures of auditory thresholds with and without conditioner pulses; and measures of electrode interactions using recordings of intracochlear evoked potentials.

- Presentation of project results at the annual Neural Prosthesis Workshop (October 28-30).
- Development of DSP (Digital Signal Processor) code to implement conditioner-pulses processors
- Further development of other hardware and software for the speech reception and evoked potential laboratories, including among many other developments (a) refinement of software for support of psychophysical scaling studies and (b) development of hardware and software for recording of intracochlear evoked potentials, along the lines indicated in QPR 9 for the prior project in this series.
- Continued analysis of psychophysical, speech reception, and evoked potential data from prior studies.
- Continued preparation of manuscripts for publication, including in this quarter two chapters for the book *Cochlear Implants: Principles, Practice and Pitfalls,* edited by John Niparko.

In this report we describe initial studies with three subjects having the same type of cochlear implant on both sides. Subjects with bilateral implants are rare, and subjects with the same device on both sides are exceedingly rare. The studies with the present subjects included psychophysical measures of sensitivities to timing and amplitude differences for stimuli delivered to electrode sites on the two sides matched for pitch (and, for the measures of timing differences, with amplitudes on the two sides matched for loudness). Additional studies with two of the subjects included evaluation of various speech processor designs, some of which presented stimuli across the two sides. The present report describes the psychophysical studies. Results from the speech reception studies will be described in a future report.

II. Pitch Discrimination among Electrodes and Interaural Timing and Amplitude Cues in Three Subjects with Bilateral Cochlear Implants

This report is being provided in two forms: a printed version suitable for monochrome photocopying and a polychrome version for posting on World Wide Web sites. Wherever color is used in the latter version, labels will refer to both, e.g. "dashed blue lines" in a plot and "yellow [light grey] highlighting" in a table.

Among users of cochlear implants, those few patients with functioning devices in both ears represent an especially valuable resource for research. Until recently the unique circumstances that led to a second implant in each case meant that such patients presented 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 were available in patients with identical devices implanted bilaterally, although a fully equivalent situation on the two sides was unlikely given the circumstances that typically led to a second, contralateral surgery. Now we are beginning to be able to study some patients with identical devices implanted bilaterally and equivalently.

Subjects

We here report some initial studies with subject NU5, the first of a series of patients to be implanted simultaneously with bilateral Nucleus CI24M transcutaneous devices as part of a study at the University of Iowa. Now 37 years of age, NU5 was first diagnosed with a hearing loss at age 18, following attendance at a rock concert. She experienced a further sudden loss during pregnancy at age 28 and subsequent gradual progressive loss until diagnosis of profound deafness at age 35. She used a hearing aid on the left side for six to seven years preceding bilateral cochlear implantation in December 1997 by Bruce J. Gantz, M.D. Equivalent depths of insertion were achieved for her electrode arrays bilaterally. Her initial week of studies at RTI took place in September 1998.

We shall compare the results of these initial studies with those of similar studies with subject ME2, who has bilateral Med-El COMBI40 transcutaneous devices implanted by Joachim Müller, M.D. at Würzburg, Germany. ME2 participated in three weeks of studies at RTI in November 1997, at age 60. He had been first diagnosed with a hearing loss at age 20 and used hearing aids from then until implantation, while experiencing slowly progressing hearing losses bilaterally. After bilateral stapedectomies performed at other clinics failed to improve his hearing, ME2 received an analog cochlear implant in his left ear in 1993 but was unable to tolerate stimulation from that device. In the fall of 1995 he received his first pulsatile device contralaterally. Pleased with his improved hearing, ME2 requested the implantation of an identical device to replace the original left ear implant, and underwent that fifth ear surgery in the fall of 1996. Full electrode insertions were achieved in both ears. Results for ME2 beyond those paralleling initial studies with NU5 (including extensive speech reception studies) will be presented in a subsequent QPR for the present contract.

We also shall compare results with ones reported previously [QPR 5 for the previous contract] for subject NU4, who has bilateral Nucleus 22 transcutaneous implants but only a partial insertion of the electrode array on her right side. 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 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 John T. McElveen, Jr., M.D.

Apparatus

Laboratory hardware and software of our own design transmitted instructions to each of the subjects' implanted receiver/stimulators.

In the case of the Nucleus CI24M and Nucleus 22 devices, this was done essentially by providing the signals identified as DAMP and OUTPUT in Figure 21 of U. S. Patent 4,532,930 for the original Nucleus prosthesis. Psychophysical testing routines were executed in real time by the same digital signal processor (DSP) used to implement speech processing strategies and 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. Differences in transmission rate between the two types of Nucleus device required some minor differences in the interface hardware.

In the case of the Med-El COMBI-40 devices, our same laboratory DSP transmitted electrode assignment, amplitude, duration, and onset timing information for each stimulus pulse to an interface designed and constructed by Stefan Brill and Otto Peter of the University of Innsbruck.

Comparisons among electrodes: Subject NU5

In our recent studies with NU5, as was the case with our two previous bilateral subjects, we began by considering all the electrodes that had been used in the subject's prior clinical fittings. Contrary to our normal practice, in this case we shall follow the convention used clinically for Nucleus devices and refer to the electrodes by numbers beginning at the *basal* end of the array. 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 L2 through L4 and L6 through L22 in the subject's left ear and R3 through R22 in the right -- twenty sites in each ear.

Stimulation amplitudes corresponding to threshold (T level) and comfortably loud (C level) were determined on our apparatus for all forty sites, using 200 ms bursts of 25 µs/phase pulses at rates of 200 p/s (pulses/s) and 800 p/s. All forty sites then were included in formal studies of pitch discrimination and ranking at each of the two rates.

Table I indicates the pulse amplitudes (in clinical units), Table Ia for the 200 p/s stimuli and Table Ib for the 800 p/s stimuli. In all cases stimulation was monopolar with respect to both implanted reference electrodes (R1+2 in clinical fitting system terms). Within the data for each pulse rate, all C levels were carefully loudness balanced across electrode locations on both sides.

Table Ia. T and C levels, 25 μs/phase, 200pps, 200ms bursts. Subject NU5.

Electrode	T level (cu)	C level (cu)		Electrode	T level (cu)	C level (cu)
L2	162	214		R3	167	211
L3	163	209		R4	163	214
L4	159	210		R5	165	214
L6	163	216		R6	166	218
L7	159	215		R7	165	215
L8	160	215		R8	164	219
1L9	162	218		R9	165	219
L10	158	215		R10	163	220
L11	160	214		R11	161	219
L12	162	215		R12	159	221
L13	159	216		R13	160	222
L14	159	216		R14	155	217
L15	155	215		R15	156	221
L16	153	210		R16	158	225
L17	158	213		R17	156	220
L18	155	216		R18	157	218
L19	154	215		R19	156	216
L20	155	210		R20	161	214
L21	156	210		R21	160	212
L22	157	209		R22	166	211

Table Ib. T and C levels, 25 µs/phase, 800pps, 200ms bursts. Subject NU5.

Electrode	T level (cu)	C level (cu)		Electrode	T level (cu)	C level (cu)
L2	138	207		R3	143	213
L3	133	208		R4	139	209
L4	128	209		R5	135	211
L6	132	209		R6	132	211
L7	135	206		R7	136	214
L8	133	206		R8	136	214
L9	128	206		R9	128	214
L10	135	206		R10	131	214
L11	130	209		R11	135	214
L12	131	209		R12	133	217
L13	129	212		R13	130	225
L14	128	212		R14	125	223
L15	135	215		R15	127	226
L16	129	212		R16	133	225
L17	134	215		R17	133	227
L18	131	212		R18	132	225
L19	133	215		R19	131	223
L20	132	212		R20	137	219
L21	134	211		R21	136	216
L22	137	211		R22	135	216

The procedure used for our initial studies of pitch discrimination and ranking has been reported previously [QPRs 1, 3, and 5 for the previous project]. A pair of 200 ms pulse bursts separated by 500 ms (200 or 800 p/s bursts of 25 µs/phase pulses, with amplitudes loudness balanced at C level) 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 the combined total of 40 electrode sites (L2-L4, L6-L22, and R3-R22) were included in single studies to assess pitch ranking over the full extent of both arrays. 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 Table II and Figs. 1 and 2. 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 IIa includes data for the 200 p/s rate and Table IIb the 800 p/s data.

All table entries equal to or greater than 80% consistent have been highlighted in yellow [light grey]. In this and all similar tables that follow, the number of presentations per condition is shown in each column, with half of those being presented in each order.

Table IIa. Bilateral Pitch Ranking, 200 ms bursts of 25 µs/phase pulses at 200 p/s. Subject NU5.

First of compared locations in list order	D=1: % consistent	D=2: % consistent	D=3: % consistent	D=4: % consistent	D=5: % consistent	D=6: % consistent
L2	42	50	58	50	58	83
R3	50	50	50	75	58	83
L3	42	50	92	67	75	83
R4	50	58	75	83	75	83
L4	67	75	83	75	67	67
R5	50	83	75	83	58	75
L6	42	58	58	100	75	100
R6	67	75	83	92	75	100
L7	50	83	83	100	92	92

Table IIa. Bilateral Pitch Ranking, 200 ms bursts of 25 µs/phase pulses at 200 p/s. Subject NU5 (*continued from previous page)*

R7	42	67	92	92	67	100
L8	42	83	58	100	100	100
R8	83	75	100	100	83	100
L9	33	67	17	100	92	92
R9	58	92	92	92	75	100
L10	67	67	75	100	100	83
R10	50	92	75	75	67	100
L11	58	75	75	100	92	100
R11	50	92	92	100	83	100
L12	50	100	42	100	83	100
R12	75	83	92	100	92	100
L13	100	92	58	100	100	100
R13	67	83	92	100	50	92
L14	50	100	42	100	100	100
R14	67	83	83	83	100	100
L15	67	75	83	100	100	100
R15	42	92	100	100	83	92
L16	75	100	75	75	100	100
R16	50	50	75	58	50	100
L17	42	75	50	75	100	100
R17	50	75	83	67	50	100
L18	42	58	58	50	83	100
R18	50	75	67	50	42	92
L19	50	58	58	58	75	92

Table IIa. Bilateral Pitch Ranking, 200 ms bursts of 25 µs/phase pulses at 200 p/s. Subject NU5.
(continued from previous page)

R19	42	58	75	67	58	100
L20	50	58	75	50	92	
R20	50	67	58	50		
L21	50	83	67			
R21	50	92				
L22	50					
R22						
Overall % consistent	53-------55	74-------76	64-------81	83-------82	88-------69	94-------95
Nature of comparisons	bilateral	unilateral (D = 1)	bilateral	unilateral (D = 2)	bilateral	unilateral (D = 3)
Number of times each comparison presented	12	12	12	12	12	12

Table IIb. Bilateral Pitch Ranking, 200 ms bursts of 25 µs/phase pulses at 800 p/s. Subject NU5.

First of compared locations in list order	D=1: % consistent	D=2: % consistent	D=3: % consistent	D=4: % consistent	D=5: % consistent	D=6: % consistent
L2	50	50	50	100	70	100
R3	50	50	50	100	90	100
L3	50	90	50	100	90	100
R4	60	70	50	100	80	100
L4	60	90	50	100	100	100
R5	50	90	50	100	100	100
L6	50	60	60	100	100	100
R6	60	100	60	100	100	100
L7	60	80	80	100	100	100
R7	40	70	50	100	100	100
L8	70	80	60	100	100	100
R8	80	80	40	100	100	100
L9	60	70	50	100	100	100
R9	50	100	60	100	100	100
L10	70	100	50	100	100	100
R10	100	100	60	100	100	100
L11	60	90	60	100	100	100
R11	80	100	90	100	100	100
L12	70	100	80	100	100	100
R12	90	100	60	100	100	100
L13	90	100	50	100	100	100
R13	70	100	60	100	90	100
L14	80	100	70	100	100	100

Table IIb. Bilateral Pitch Ranking, 200 ms bursts of 25 µs/phase pulses at 800 p/s. Subject NU5.
(continued from previous page)

R14	50	100	50	80	90	100
L15	90	50	80	100	100	100
R15	40	80	60	90	80	100
L16	70	80	50	100	100	100
R16	30	100	50	100	90	100
L17	50	70	50	80	100	100
R17	40	70	50	100	50	100
L18	50	50	50	70	100	100
R18	50	90	50	90	50	100
L19	50	60	50	90	100	100
R19	50	80	50	100	50	100
L20	50	50	50	100	100	
R20	50	90	60	90		
L21	50	70	50			
R21	50	60				
L22	50					
R22						
Overall % consistent	62--------57	71--------86	57--------51	97--------97	98--------86	100----100
Nature of comparisons	bilateral	unilateral (D = 1)	bilateral	unilateral (D = 2)	bilateral	unilateral (D = 3)
Number of times each comparison presented	10	10	10	10	10	10

It is important to note, when examining Table II, that any "% consistent" scores significantly *below* 50 would denote discrimination and ranking in a pitch order *counter* to that of the arbitrary bilateral list. In the D = 1 column such values could serve as the basis for reordering the list. The only instance of this in Table II, however, is highlighted purple [darker grey] in the D = 3 column of Table IIa, with respect to electrode L9 at 200 p/s where the score was 17%. This result would indicate that stimulation of L9 produces percepts that are significantly lower in pitch than for R10. An inconsistency arises, however, when one notes that the pitches associated with stimulation of L11 and R10 are indistinguishable (50%) while L9 stimuli clearly produce percepts that are higher in pitch than those of L11 (100%). We plan further investigation of the L9 - R10 comparison when this subject next visits our lab, but for now see no basis for altering the ordering of electrodes in the 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.

In Figure 1, pairs of dots corresponding to electrodes that are discriminable on the basis of pitch are connected by lines that are also colored in some versions of this report -- solid purple indicating pitch ranking scores of 90% or above, and dashed blue indicating scores between 80% and 89%. In this figure the basalmost electrodes -- those corresponding to the highest pitch percepts -- are represented at the top of the diagram; this will be done consistently in Figures 1 through 6, regardless of the particular electrode numbering convention being followed. For each electrode in Figures 1, 3, and 5 of this report we have searched for the nearest contralateral and ipsilateral electrodes in the pitch-ranked list that are discriminably higher and lower in pitch. Thus four lines will terminate in each dot for which all those criteria were satisfied. Any set of clearly discriminable electrodes should be connected by lines in such a figure.

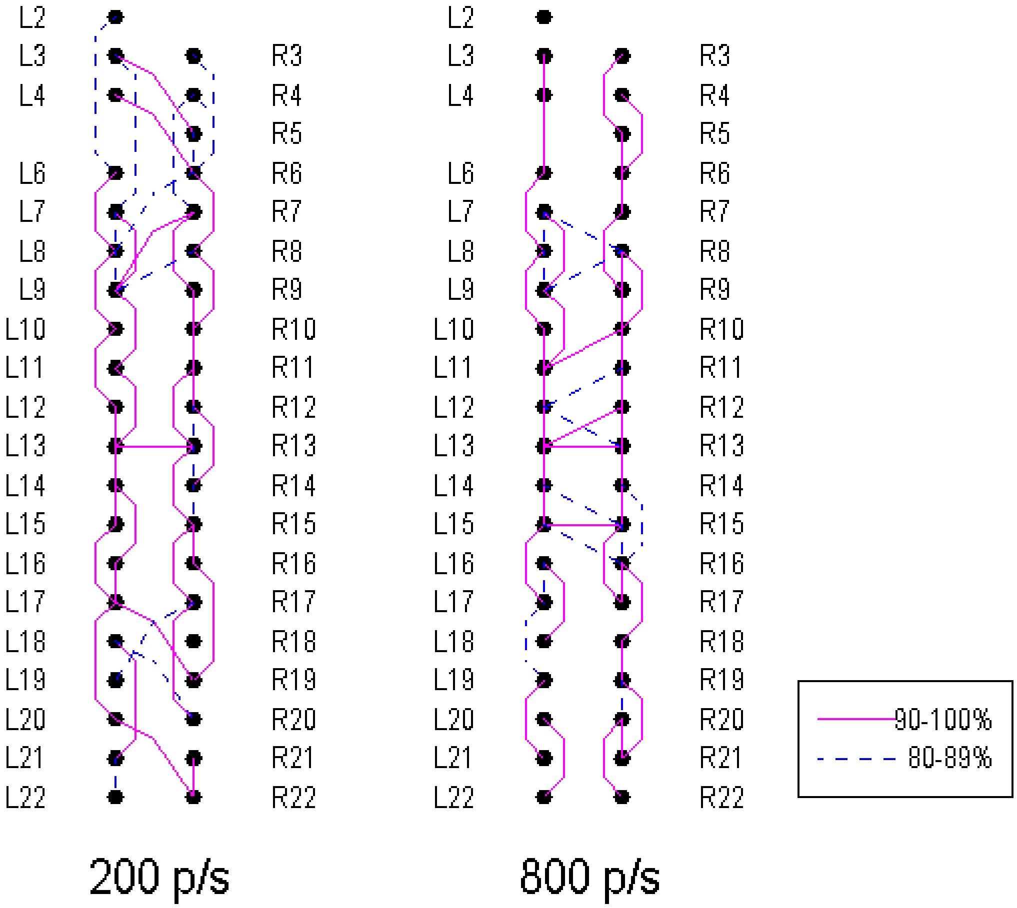

Figure 1. Pairs of electrodes discriminable on the basis of pitch. Subject NU5.

These data indicate the availability of as many as 11 pitch-discriminable channels of stimulation on the left side and 13 on the right for 200 p/s, and 13 on the left and 16 on the right for 800 p/s.

Figure 2, on the other hand, indicates pairs of electrodes that are indistinguishable on the basis of pitch, with solid red lines indicating pairs for which the above ranking scores were exactly 50%, together with the additional pairs connected by dashed black lines comprising all those with scores between 40% and 60%.

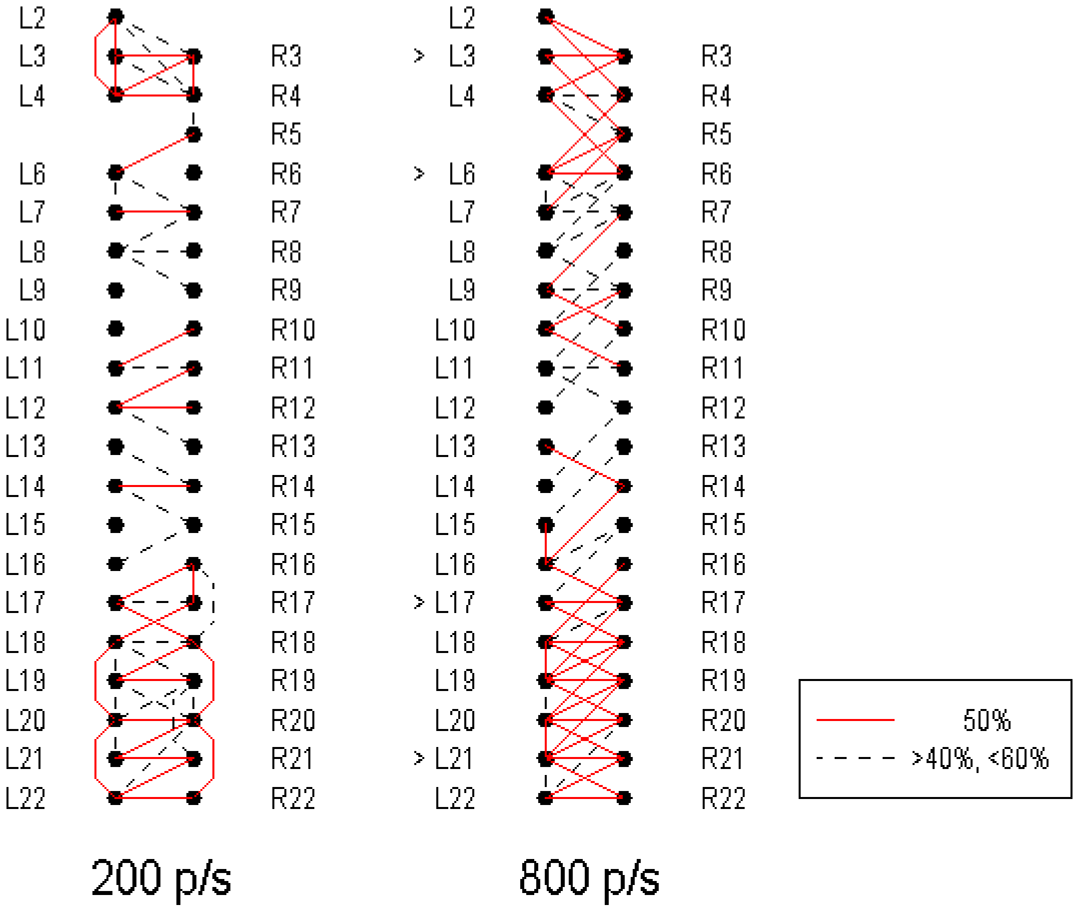

Figure 2. Pairs of electrodes indiscriminable on the basis of pitch. Subject NU5.

Notice the substantial number of bilateral pairs of electrode sites capable of supporting interaural comparisons with no perceptible difference in pitch. Four such pairs -- L3-R3, L6-R6, L17-R17, and L21-R21, marked by the symbol > in Figure 2 -- were selected for studies of this subject's ability to lateralize sounds on the basis of interaural timing and intensity differences.

Comparisons among electrodes: Subject ME2

In the case of this subject's implanted devices the clinical practice is the same as our normal convention, numbering the electrodes from the *apical* end. We will follow that convention in reporting studies with this subject, adding a prefix to each electrode label to indicate the ear in which it is implanted. Each of ME2's implanted devices gave us access to 8 active electrodes, and we began by determining stimulation amplitudes corresponding to threshold and most comfortable loudness (MCL) for all sixteen sites, using 200 ms bursts of 70 µs/phase pulses at 2000 p/s. All sixteen sites then were included in formal studies of pitch discrimination and ranking at MCL.

Table III indicates the pulse amplitudes (in µa, based on our own calibration) corresponding to threshold and MCL. Stimulation was monopolar with respect to the standard clinical reference electrode. All MCL amplitudes were carefully loudness balanced across electrode locations on both sides.

Table III. Threshold and MCL levels, 70 µs/phase, 2000p/s, 200ms bursts. Subject ME2.

Electrode	Threshold (µa)	MCL (µa)		Electrode	Threshold (µa)	MCL (µa)
L1	74	277		R1	59	183
L2	96	293		R2	69	245
L3	49	227		R3	57	183
L4	45	220		R4	88	329
L5	51	306		R5	96	311
L6	61	351		R6	60	270
L7	99	440		R7	72	301
L8	89	341		R8	109	377

The same procedure described for subject NU5 was used to rank ME2's electrodes by pitch, across both his left and right ear arrays. All sixteen sites were included in a single study, L1-L8 and R1-R8. In numerical order (in this case apex to base) 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. The stimuli were the MCL signals described in Table III.

Results of these pitch ranking studies are summarized in Tables IV and V and Figures 3 and 4. Again, a "consistent" response is one indicating that pitch ranking is consistent with the order of the list being evaluated. Again, all table entries equal to or greater than 80% consistent have been highlighted in yellow [light grey] and those less than or equal to 20% in purple [darker grey].

Table IV. Bilateral Pitch Ranking, 200 ms bursts of 70 µs/phase pulses at 2000 p/s. Subject ME2.

First of compared locations in list order	D=1: % consistent	D=2: % consistent	D=3: % consistent	D=4: % consistent	D=5: % consistent	D=6: % consistent
L1	60	100	100	100	100	100
R1	65	65	100	100	100	100
L2	50	100	100	100	100	100
R2	100	100	100	100	100	100
L3	0	100	100	100	100	100
R3	100	100	100	100	100	100
L4	20	100	100	100	100	100
R4	100	100	100	100	100	100
L5	35	100	100	100	100	100
R5	100	100	100	100	100	100
L6	5	100	100	100	100	
R6	100	100	100	100		
L7	0	95	100			
R7	100	95				
L8	15					
R8						
Overall % consistent	23-------95	99-------94	100----100	100----100	100----100	100----100
Nature of comparisons	bilateral	unilateral (D = 1)	bilateral	unilateral (D = 2)	bilateral	unilateral (D = 3)
Number of times each comparison presented	20	20	4	4	4	4

In this case, results in the D = 1 column of Table IV indicate clearly that the initial arbitrary list order must be changed in order to be consistent with the observed pitch rankings. Once interpreted in terms of the corrected list order, the same pitch ranking data present a very consistent picture, as demonstrated in Table V.

Table V. Same data as Table IV with List Reordered. Subject ME2

First of compared locations in list order	D=1: % consistent	D=2: % consistent	D=3: % consistent	D=4: % consistent	D=5: % consistent	D=6: % consistent
L1	60	100	100	100	100	100
R1	65	65	100	100	100	100
L2	50	100	100	100	100	100
R2	100	100	100	100	100	100
R3	100	100	100	100	100	100
L3	100	100	100	100	100	100
R4	80	100	100	100	100	100
L4	100	100	100	100	100	100
R5	65	100	100	100	100	100
L5	100	100	100	100	100	100
R6	95	100	100	100	100	
L6	100	100	100	100		
R7	100	95	100			
L7	100	95				
R8	85					
L8						
Overall % consistent	87-------86	99-------94	100----100	100----100	100----100	100----100
Number of times each comparison presented	20	20	4	4	4	4

[Notice that when the list has been reordered, as in Table V, even and odd values of D no longer correspond to purely unilateral and bilateral conditions, respectively.]

In Figure 3, the pairs of dots corresponding to electrodes that are discriminable on the basis of pitch are connected by colored lines. As in Figure 1, solid purple indicates pitch ranking scores of 90% or above, and dashed blue indicates scores between 80% and 89%.

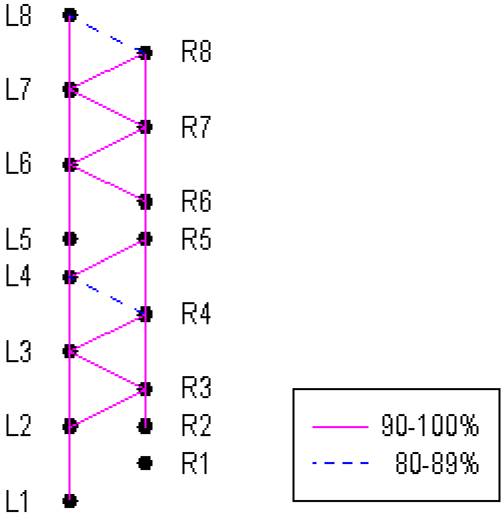

Figure 3. Pairs of electrodes discriminable on the basis of pitch. Subject ME2.

These data indicate the availability of as many as 8 pitch-discriminable channels of stimulation on the left side and 7 on the right for this pulse rate and duration, and a total of 13 pitch-discriminable channels when both ears are considered together.

Figure 4, like Figure 2, indicates pairs of electrodes that are indistinguishable on the basis of pitch, with solid red lines indicating pairs for which the ranking scores were exactly 50%, together with the additional pairs connected by dashed black lines comprising all those with scores between 35% and 65%.

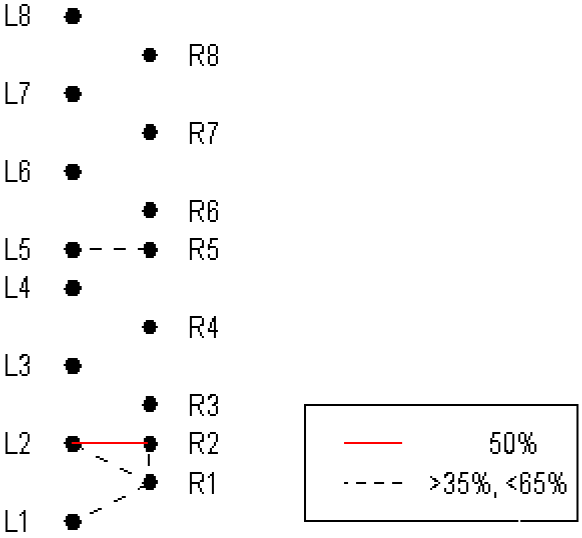

Figure 4. Pairs of Electrodes indiscriminable on the basis of pitch. Subject ME2.

Notice the three independent pairs of electrode sites capable of supporting interaural comparisons with no perceptible difference in pitch, at least for this pulse rate and duration. Two such pairs, L5-R5 and L2-R2, were selected for studies of this subject's ability to lateralize sounds on the basis of interaural timing and intensity differences.

Comparisons among electrodes: Subject NU4

Initial T and C level measurements and bilateral pitch ranking results for Subject NU4 have been reported previously [QPR 5 for the previous contract]. Figure 5, like Figures 1 and 3 for the other two subjects, shows pairs of electrodes discriminable on the basis of pitch.

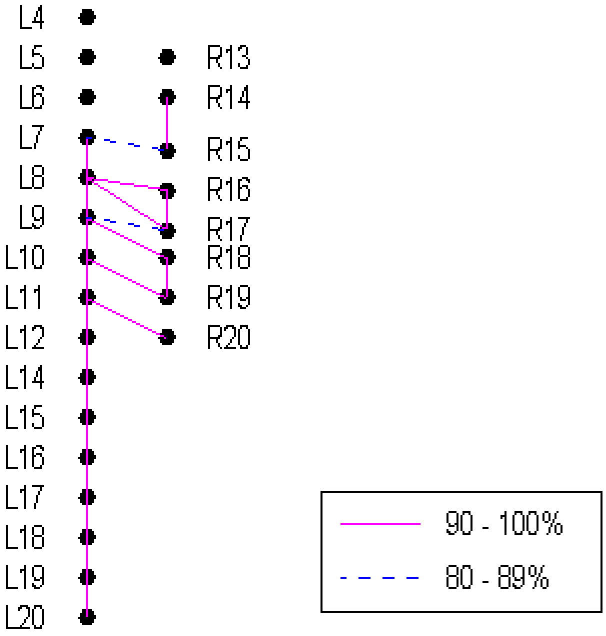

Figure 5. Pairs of Electrodes discriminable on the basis of pitch. Subject NU4.

These results indicate the availability of as many as 13 pitch discriminable channels of stimulation on the left side and 4 on the right side. When both sides are considered together, a total of 14 pitch-discriminable channels are available.

Figure 6, like Figures 2 and 4 for the other two subjects, shows pairs electrodes found to be indiscriminable on the basis of pitch.

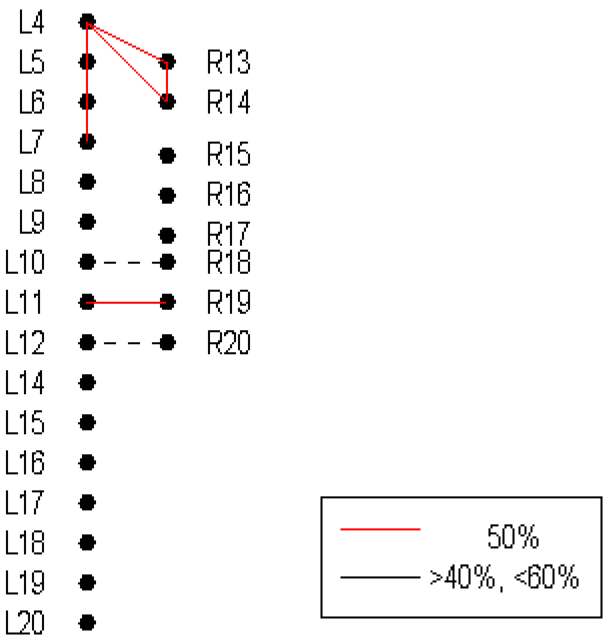

Figure 6. Pairs of Electrodes indiscriminable on the basis of pitch. Subject NU4.

Notice the four independent pairs of electrode sites capable of supporting interaural comparisons with no perceptible difference in pitch, at least for this pulse rate and duration. Three such pairs -- L10-R18, L11-R19, and L12-R20 -- were selected for studies of this subject's ability to lateralize sounds on the basis of interaural timing and intensity differences.

Interaural delay studies

Our studies of each subject's ability to make use of interaural delay information also have been based on a two alternative forced choice task, one in which a 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 (Nucleus devices) or MCL (Med-El devices): 200 ms bursts of pulses at the rates and durations evaluated for each subject, 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.

In the case of Subject NU5, such studies were conducted with four pitch-matched bilateral pairs of electrodes, using 25 μs/phase pulses at 800 p/s. The results are summarized in Figure 7, where percent correct lateralization scores from the chance level of 50% to 100% are plotted as a function of interaural delay in microseconds. There were 40 presentations in each condition.

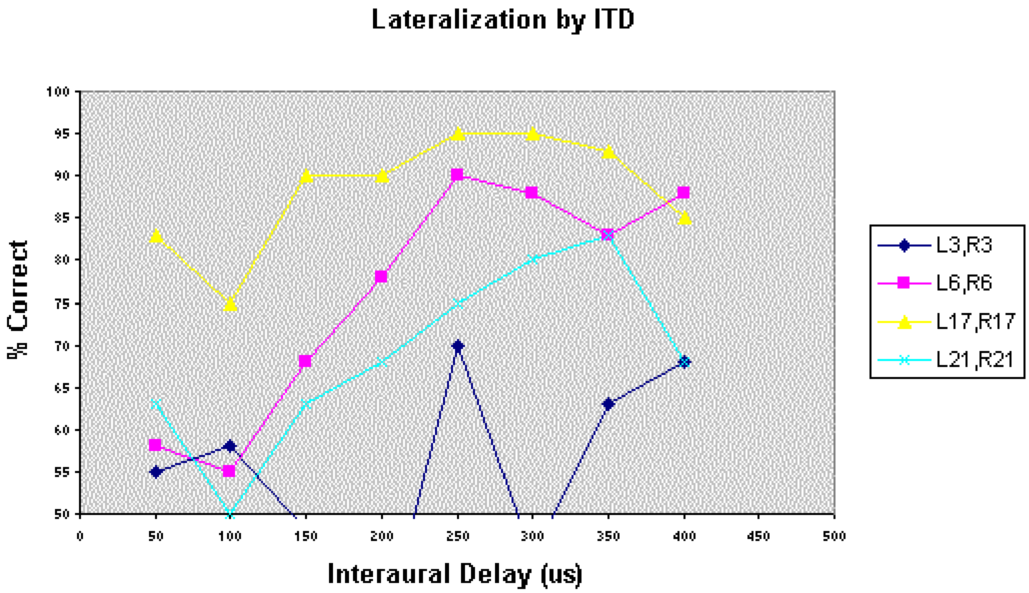

Figure 7. Lateralization from Interaural Delay: Subject NU5.

The most sensitive to interaural delay among the four bilateral pairs is the relatively apical pair -- L17-R17. For that pair, NU5 can reliably lateralize pulse bursts with an interaural delay of 50 µs, the smallest we were able to produce with our equipment at the time of these studies. The pair least sensitive to interaural delay is the basalmost L3-R3, which requires delays of about 450 µs or more for reliable lateralization. Such a delay corresponds to a 45 degree angle of incidence. The remaining two pairs -- L6-R6 and L21-R21 -- are characterized by similar intermediate sensitivities, reliable for delays equal to or greater than about 150 µs. Such a delay corresponds to an angle of incidence of about 15 degrees to left or right.

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 50 µs. For a 9 cm head radius, a 50 µs difference in arrival time at the two ears corresponds to incidence from only about 5 degrees to one side. Our results for all four electrode pairs in this subject represent much greater sensitivities than those 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).]

Our previously reported results of similar studies with Subject NU4 are shown to the same scales in Figure 8. In these cases the stimuli were 50 ms bursts of 80 µs/phase pulses delivered at a rate of 480 p/s. Data from 80 presentations at each delay are included for the L10-R18 pair, 120 for L11-R19, and 60 for L12-R20.

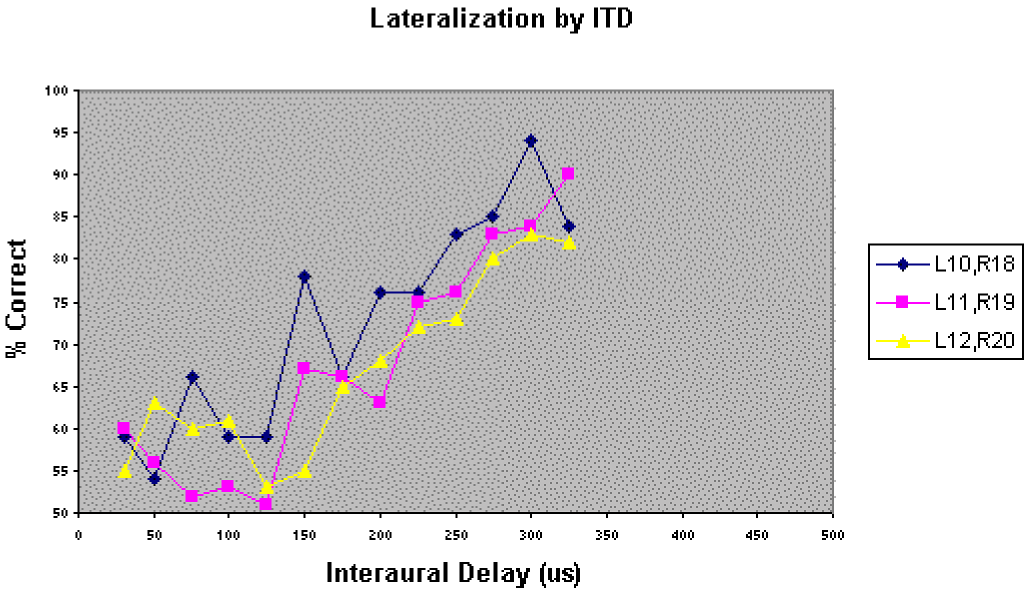

Figure 8. Lateralization from Interaural Delay: Subject NU4.

In the case of this subject, all three bilateral electrode pairs studied had sensitivities resembling those of the two intermediate pairs just described for Subject NU5.

Finally, the most sensitive condition we were able to find for Subject ME2 used bilateral pitch-matched electrode pair L2-R2 and 100 µs/phase pulses at a rate of only 40 p/s. Results for 20 presentations in each such condition are shown in Figure 9.

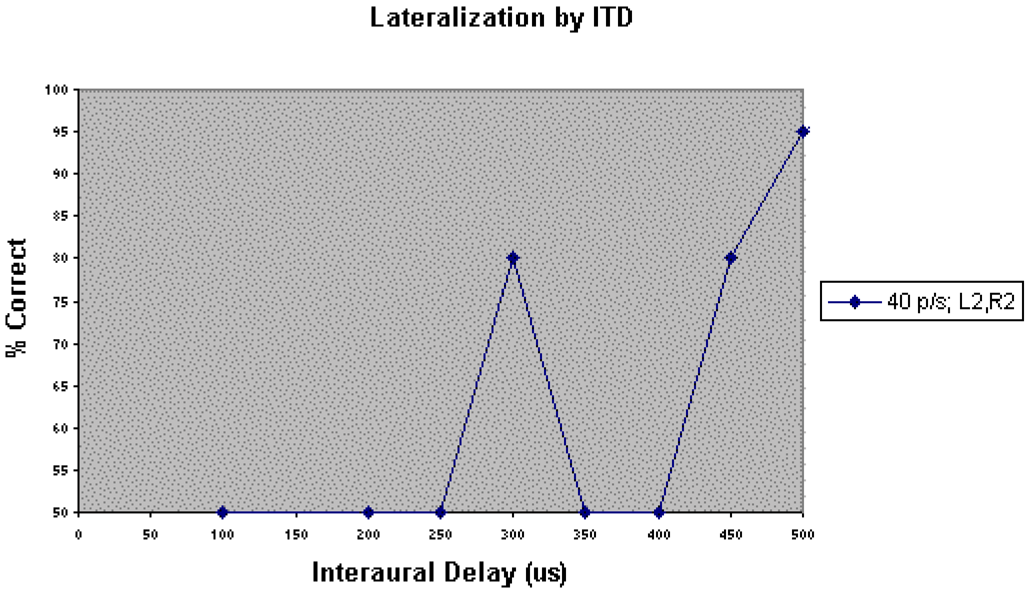

Figure 9. Lateralization from Interaural Delay: Subject ME2.

Except for the anomalously high sensitivity at a delay of 300 µs (verified by retest), these results resemble those for the least sensitive of Subject NU5's four studied pairs, being reliable for lateralization for delays of 450 µs or more. Figure 9 uses the same scale of interaural delay as Figures 7 and 8 to facilitate comparisons among the three subjects. Figure 10 displays the same results for this subject, but includes data for longer delays, better indicating the context.

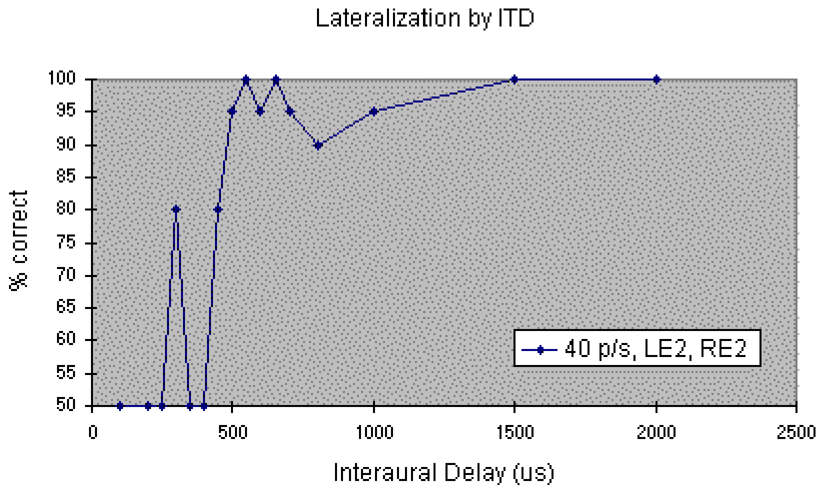

Figure 10. Lateralization from Interaural Delay: Subject ME2.

Similar studies with Subject ME2 using a variety of stimuli, including 200 ms bursts of pulses at 2000 p/s with a duration of 70 µs/phase and 20 Hz and 40 Hz modulation of a 2000 p/s carrier, found that lateralization scores dropped to chance quite rapidly for interaural delays approaching 1500 µs, representing sensitivities similar to those reported by van Hoesel *et al.* Results for 20 presentations in each condition are shown in Figure 11.

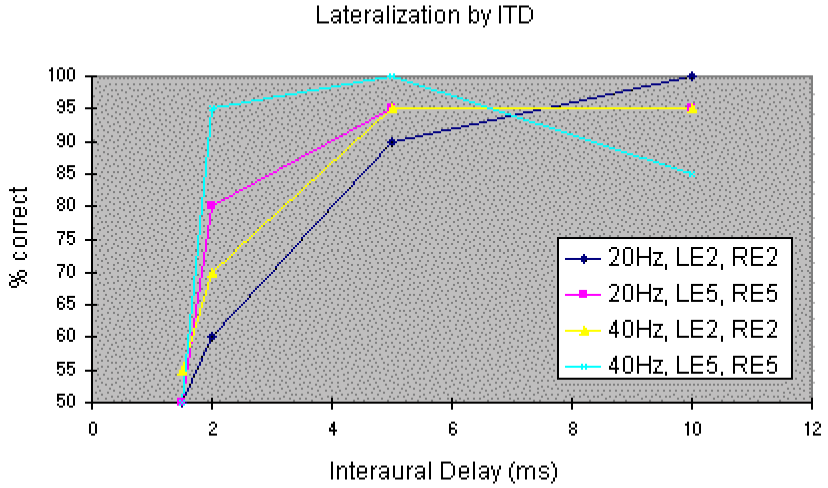

Figure 11. Lateralization from Interaural Delay: Subject ME2

Interaural amplitude difference studies

Studies of each subject's ability to utilize interaural amplitude differences also have been conducted, 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.

For Subject NU5, amplitude lists were constructed for electrode pairs L3-R3, L6-R6, L17-R17, and L21-R21 using C levels for 200 ms bursts of 25 µs/phase pulses at a rate of 800 p/s. The lists covered differences of from 1 to 6 cu at intervals of 1 cu. Results for 40 presentations of each condition are shown in Figure 12.

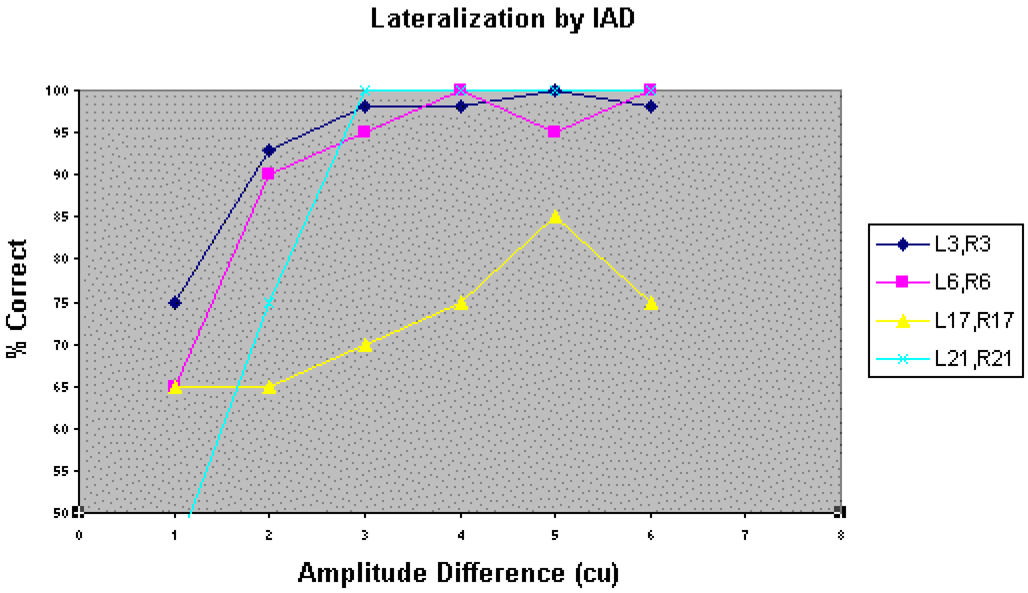

Figure 12. Lateralization from Interaural Amplitude Difference: Subject NU5.

This subject is able reliably to lateralize a C-level percept on the basis of 1 to 2 cu differences in pulse amplitude for three of the four electrode pairs studied. One of the four (L17-R17) is significantly less sensitive than the others. A 1 cu difference corresponds to about 1/75 of this subject's dynamic range for electrical stimulation with these stimuli.

For Subject NU4, 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. Results for 8 presentations in each condition are shown in Fig. 13.

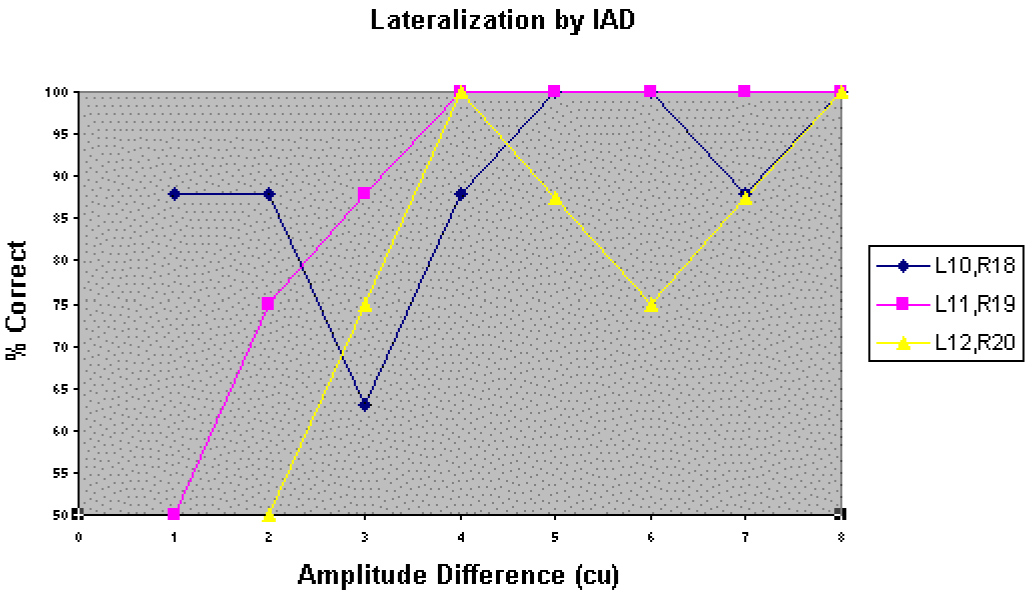

Figure 13. Lateralization from Interaural Amplitude Difference: Subject NU4.

This 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. 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. Based on calibration data from the manufacturer of the implanted devices, this difference corresponds to only about 1/75 of her overall dynamic range for electrical stimulation.

For Subject ME2, amplitude lists for L2-R2 were constructed to cover amplitude differences of from 1 to 8 cu at intervals of 1 cu. Simultaneous bilateral 200 ms bursts of 70 µs/phase pulses at 2000 p/s were used. Results for 10 presentations in each condition are shown in Figure 14.

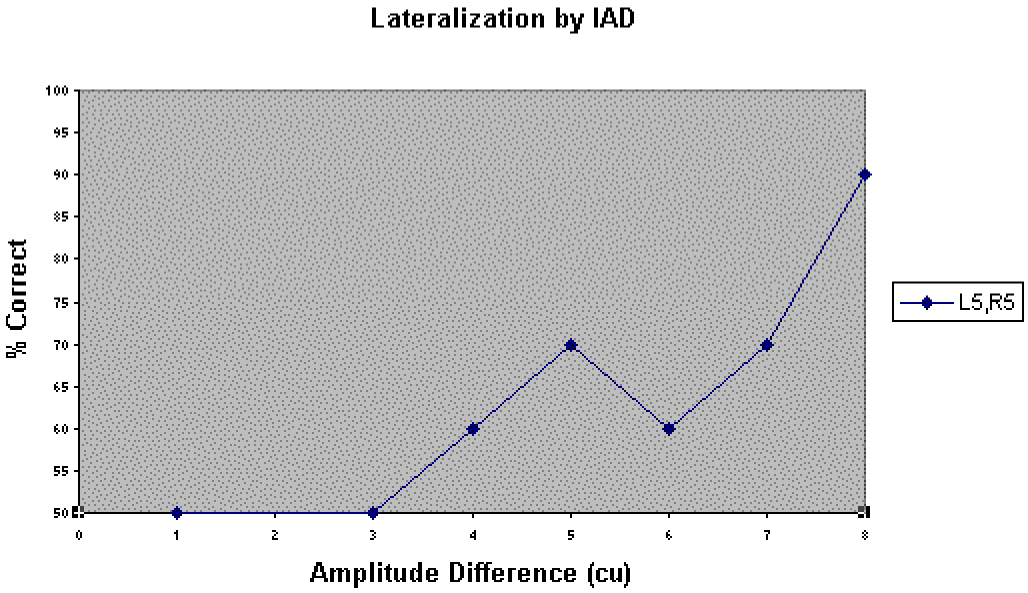

Figure 14. Lateralization from Interaural Amplitude Difference: Subject ME2.

This subject is able reliably to lateralize a MCL sound percept on the basis of a 5 cu difference in pulse amplitude. Based on calibration data, this corresponds to a difference of about 1/30 of his overall dynamic range for electrical stimulation.

Summary

Across nine pitch and loudness matched contralateral electrode pairs in three subjects, we have observed the ability to lateralize reliably on the basis of interaural time delay in one case on the basis of a 50 µs delay, in five cases on the basis of a 150 µs delay, in two cases on the basis of a 450 µs delay, and in two cases on the basis only of delays exceeding about 1500 µs. One of the 450 µs cases was for one particular low-rate stimulus to an electrode pair that otherwise required a 1500 µs delay to support lateralization. In terms of angle of incidence, the 450, 150, and 50 µs delays correspond to about 45°, 15°, and 5°, respectively. There appears to be great potential for the use of interaural time delays to convey information via electrical stimulation with bilateral implants, but there also appears to be enormous variation in the ability to detect such delays across subjects and electrode sites.

Across eight pitch matched contralateral electrode pairs in three subjects, we have observed the ability to lateralize reliably on the basis of interaural pulse burst amplitude in four cases on the basis of 1 to 2 clinical unit differences in amplitude, in two cases on the basis of 3 to 4 clinical unit differences, and in the remaining two cases on the basis of 5 clinical unit differences. As a fraction of total dynamic range for electrical stimulation (threshold to MCL or C-Level) these amplitude differences correspond to 1/30 to 1/75, or about 1.5 to 3 percent. There appears to be substantial potential for the use of interaural amplitude differences to convey direction of sound incidence via electrical stimulation with bilateral cochlear implants.

Results from further studies with these and other bilateral implant subjects will be presented in future reports.

III. Plans for the Next Quarter

Our plans for the next quarter include the following:

- A visit by Thomas Lenarz, M.D., Ph.D., and Rolf Battmer, Ph.D., of the Medizinische Hochschule Hannover, on February 12.
- Studies with Clarion subject MI-4, January 11-15, to (a) evaluate various combinations of processing strategies and electrode coupling configurations and (b) include this subject in our ongoing comparisons of pitch scaling limits and speech reception scores.
- Studies with Ineraid subject SR16, January 25-29, including additional scaling studies like those conducted with subjects SR2, SR10 and SR15 in the present quarter, and completing longitudinal measures of speech reception performance with this subject’s portable CIS processor.
- Ongoing studies with Ineraid subject SR2. Beginning in February, this subject will be able to spend two full days per week in studies in our laboratory, compared with the half days he has been spending with us. The additional time presents a grand opportunity for increasing the depth and breadth of studies with this subject, who possesses exceptional reporting skills. Plans for studies with this subject in the next quarter include further scaling and forward masking experiments, as suggested by results from experiments just completed, and evaluation of a wide range of speech processor designs, included detailed evaluation of "conditioner pulses" processors.
- Further studies with bilateral subject NU-5, March 29 to April 1, to evaluate speech processor designs. (Results from psychophysical studies with this subject are presented in this present report.)
- Participation in a course on C++ object programming by Marian Zerbi, March 16-19.
- Continued analysis of psychophysical, speech reception, and evoked potential data from prior studies.
- Continued preparation of manuscripts for publication.

IV. Acknowledgments

We thank subjects SR2, SR10, and SR15 for their participation in the studies conducted during this quarter, and subjects ME2, NU4, and NU5 for their participation in the earlier studies reported here.

Appendix 1. Summary of Reporting Activity for this Quarter

Reporting activity for this quarter, covering the period of September 30 through December 31, 1998, included the following:

Invited Lecture

Wilson BS: Speech processors for auditory prostheses. Neural Prosthesis Workshop, Bethesda, MD, October 28-20.

Publications

Lawson DT, Wilson BS, Zerbi M, van den Honert C, Finley CC, Farmer JC Jr, McElveen JT, Roush PA: Bilateral cochlear implants controlled by a single speech processor. Am J Otol 19: 758-761, 1998.

Rubinstein JT, Wilson BS, Finley CC, Abbas PJ: Pseudospontaneous activity: Stochastic independence of auditory nerve fibers with electrical stimulation. Hearing Res 127: 108-118, 1998.