First Quarterly Progress Report

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Speech Processors for Auditory Prostheses

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CONTENTS

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 can be used to evaluate the ability of speech processing strategies to produce desired spatial or temporal patterns of neural activity.

Work and activities in this quarter included:

- Continuing studies with local subject ME-12, implanted bilaterally with Med-El Tempo+ devices.
- Visits and presentations by seven candidates for positions within the Center for Auditory Prosthesis Research, culminating in the hiring of Dr. Xiaoan Sun to join the group in August as an electrical engineer.
- Two weeks of studies with percutaneous subject SR-3 (May 14 - 23), who uses a Med-El CIS-Link processor with her Ineraid implanted electrodes.
- Participation by Reinhold Schatzer in the International Conference on Acoustics Speech and Signal Processing, May 13 - 17, in Orlando FL.
- Invited presentation by Dewey Lawson as part of the annual Prentice Bloedel Day (May 20) at the Virginia Merrill Bloedel Hearing Research Center of the University of Washington in Seattle. The presentation was part of a gala program honoring Francis A. Spelman, long time research affiliate of the Center.
- Two weeks of studies (June 3 - 14) with subject NU-6, implanted bilaterally with Cochlear Corp. Nucleus 24 devices.
- A visit June 6 - 7 by Dr. Joachim Müller, head of clinic in the Department of Otolaryngology of the University of Würzburg.
- A June 6 visit and lecture by Dr. Enrique A. Lopez-Poveda of the Medical Faculty of the University of Castille - La Mancha. During the visit, Dr. Lopez-Poveda agreed to become a consultant to this project, and we are delighted to announce that his appointment is now official.
- Three weeks of studies with ME-15, a new subject implanted bilaterally with Med-El devices and now using Tempo+ processors along with external microphones and mixing circuits of his own design (June 17 - 28).

In this report we describe recent work with bilateral subjects NU-6 and ME-15. The results from other work done this quarter will be included in subsequent reports.

II. Pitch-matched and pitch-distinct electrode pairs in bilaterally implanted arrays

Background

Throughout the time we have been studying the potential benefits of bilateral cochlear implants, we have looked for two somewhat inconsistent attributes in each new research subject.

On the one hand, we have hoped to find contralateral pairs of electrodes that were exactly matched in terms of pitch percept, in an effort to minimize other differences in our studies of the ability of subjects to lateralize sounds on the basis of interaural time and amplitude (loudness) differences (ITD and IADs). Some of our early subjects were found to have several such matched pairs, and in a few cases they even included locations near the apical and basal ends of the arrays and near the middle. In other cases, as few as only one matched pair was available for such studies.

On the other hand, we have been interested in the potential benefits of increasing the number of pitch distinct stimulation sites by utilizing electrodes from both sides, in the service both of single monophonic speech processors, and of pairs of processors applied stereophonically. After determining pitch ranking among the combined electrodes from both sides for each of our early subjects, we would look for subsets of electrodes that might form the basis for comparisons between otherwise identical processors that, for instance, utilized identical numbers of channels and channel-associated frequency analysis bands and either (a) associated a pitch matched bilateral pair of electrodes with each band or (b) used pitch distinct electrodes for stimulating the left and right sides by each channel. The number of bands and channels that could be considered on each side for such studies, of course, depended on the pitch ranking pattern among the electrodes for each research subject. Among our early patients that number tended to be a relatively small fraction of the total number of electrodes available on each side.

The two bilaterally implanted subjects most recently studied in our laboratory happen to have allowed us to examine extreme cases in terms of availability of pitch matched pairs and pitch distinct stimulation sites across the two sides. One of the subjects has 8 contralateral pitch-matched pairs, while for the other subject each electrode elicits a unique, distinct pitch percept. In the case of the first of these subjects, bilateral Nucleus 24 devices allowed us, for instance, to compare 8 channel processors using contralateral pairs of electrodes that were either all pitch matched or all quite pitch distinct, and provided excellent electrode pairs for interaural time and amplitude difference cues at locations spanning a large fraction of the overall electrode range. In the case of the other of these subjects, each of the 22 usable Med-El electrodes -- 11 on each side -- was associated with a distinct pitch percept, allowing exploration of processors with up to 22 independent frequency analysis bands each associated with a pitch distinct stimulus electrode. ITD and IAD studies were conducted with both these most recent subjects, including studies of the dependence of those variables on electrode offset with respect to a pitch matched condition. We also have been able to compare the performance of otherwise equivalent processors with all four possible combinations of (1) analysis bands that are either identical on the two sides or designed so that the edges between adjacent bands on one side fall at the center frequencies of the contralateral analysis bands and (2) pitch matched or pitch distinct contralateral pairs of electrodes.

Subjects

Subject NU-6 was first seen in our laboratory in September 2000 at age 61, having received bilateral Nucleus CI24M implants at the University of Iowa in June 1999. Her hearing loss had begun at age 9, coincident with a case of poliomyel(oencephal)itis and she reported a strong family history of deafness. She had begun use of hearing aids in her mid twenties and been diagnosed as profoundly deaf in her left and right ears at ages 58 and 59, respectively. At the time of our first studies with NU-6, she was employed as a high school teacher's aid, having formerly been a teacher for classes ranging in age from kindergarten to high school. When she returned to our laboratory in June 2002 she was employed as a school principal and reported an ability to localize sounds, including the voices of children within a classroom.

Subject ME-15 spent an initial two-week visit in our laboratory during June 2002. A retired engineer whose hobbies include skiing and serving as a crew member on prolonged sea voyages under sail, he was implanted at the HNO-Klinik Magdeburg with a Med-El Combi 40+ device on the left side in 1996 (partial insertion), a Tempo+ device on the right in 1999, and a Tempo+ replacement device on the left in 2000. (The original left side device had malfunctioned; the replacement surgery also achieved a full insertion on that side). Born in 1948, ME-15 had normal hearing until he experienced a sudden loss in 1986. At that time he was diagnosed as profoundly deaf on the left side and began to use a behind-the-ear (BTE) aid on the right, where hearing loss fluctuated until becoming profound in 1995. During that interim period a variety of medical therapies were tried, to no avail. A citizen of Germany, he owns his own fitting system and programs his own processors. Troubled by wind noise at his BTE microphones aboard sailing ships and while skiing, this subject developed his own elegant system of in-the-canal (ITC) microphones and body-worn electronics that inject signals into his Tempo+ BTE devices for processing. He reported that use of the ITC microphones produces dramatic improvements in the presence of such noise. His custom system also includes induction coils as inputs from assistive devices, and a stereo-mono switching option. He reported an ability to localize audible fog signals from other ships while on watch, and said that he enjoys movies with stereo sound tracks, especially when he can listen to them through headphones.

Pitch Percepts and Electrodes

During the initial visit of NU-6 we had identified 8 pitch matched bilateral pairs of electrodes from among the 22 available locations on the left side and 20 on the right. On her recent return visit we conducted a more intensive search for pitch matched bilateral pairs using an adaptive procedure [see Fig. 2 of QPR 12 for NIH contract N01-DC-8-2105]. Again, 8 pairs were identified, but only two of them were among the pairs identified earlier (L4-R5 and L12-R12). Four of the new pairs differed from a previous one only in the offset of a single location on one side (L2-R2 v. L1-R2 previously, L10-R11 v. L10-R10, and L15-R15 v. L15-R16) or both sides (L17-R18 v. L16-R17). Two new pairs were identified near the basal end of the array (L3-R3 and L7-R7), while two previously observed at the apical end (L19-R19 and L20-R21) were not identified as pitch matched by the adaptive procedure.

The most recent pitch ranking data for NU-6 are summarized in Figure 1, along with equivalent data for ME-15. These rankings are based entirely on comparisons using the adaptive procedure.

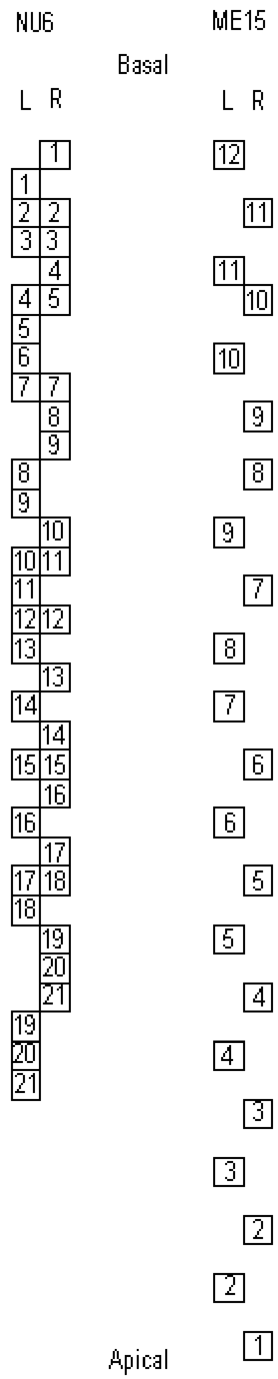

Figure 1. Summary of pitch ranking data obtained in June 2002 for subjects NU-6 and ME-15. Vertical position indicates relative pitch percepts evoked via each electrode, with higher pitches toward the top of the diagram, corresponding to the basal end of the tonotopic cochlea. Electrode numbering corresponds to the conventions of the respective manufacturers. Left and right ear electrodes are shown in separate left and right columns for each subject. Differences in vertical position between data for the two subjects are meaningless.

Most of the adaptive procedure tests involved contralateral electrode pairs. While the same procedure was used to establish pitch ranking between selected ipsilateral pairs of adjacent electrodes in the case of NU-6 (*e.g.* L7-L8, R8-R9) and the relative strength of its indications supports additional rankings reflected in Figure 1 (*e.g.* L19-R20, L19-R21, L20-R21), discriminability between every adjacent ipsilateral pair has not been demonstrated. Electrode separation along the array is approximately 0.8 mm in the case of NU-6's implants and 2.4 mm for ME-15's. As suggested in the diagram, while no pitch matched electrode pairs were found for ME-15, the pair R10-L11 came the closest and that pair was chosen as the reference for his ITD studies.

Processor Designs

Given the opportunities and limitations of these two quite different patterns of pitch ranking among implanted electrodes, we designed two distinct assignments of electrodes to processing channels for each of these subjects. These are illustrated schematically in Figure 2, where the diagrams of Figure 1 are shown without electrode number labels, but with shading indicating assignments to processor channels. The electrodes assigned to odd and even numbered channels are colored or shaded differently to make it easier to identify contralateral pairs assigned to corresponding channels. Diagrams (a) and (b) illustrate designs for NU-6 and diagrams (c) and (d) those for ME-15.

Three of these four designs are for eight channel processors. Subject NU-6 allows a direct comparison of eight channel processors between the use of only pitch matched contralateral pairs of electrodes (a), and the use of only pitch distinct contralateral pairs (b). A slight possible complication of this comparison involves two pairs of channels in the pitch distinct case. (Channels are numbered in order of ascending analyzed frequency band, *i.e.* from bottom to top in Figure 2.) The percepts for channels 4 and 5 overlap (the perceived pitch for the left side channel 5 is lower than for the right side channel 4) and channels 6 and 7 share a pitch matched pair (left side channel 7 and right side channel 6). Even that imperfection is avoided in the eight channel processors designed for ME-15 (c), where the electrodes of each contralateral pair are pitch distinct from each other **and** tonotopically pitch distinct from adjacent pairs. Finally, the same criteria are embodied in another processor for ME-15, one with eleven pitch distinct bilateral channels.

In addition to the comparison of bilateral processors using pitch matched electrode pairs to similar processors using pitch distinct pairs, we also designed studies for these two subjects to compare processors that operated synchronously on the two sides to processors that operated asynchronously, and to compare processors with identical analysis frequency bands on the two sides to processors with mutually overlapping analysis bands. The parameter values selected to support these various comparisons are summarized in Table I below. For synchronous bilateral processors, the same channels on both sides always were pulsed simultaneously at the same rate. Asynchronous cases were obtained for comparison by using slightly different rates on the two sides -- a 5 p/s difference for the 8 channel comparisons and a 3 p/s difference for 11 channel ones. All laboratory processors for both subjects used full wave rectification and 4th order, 200 Hz low pass smoothing filters. NU-6's processors used pulse widths of 28 µs/phase, while the width for pulses in ME-15's laboratory processors was 30µs/phase. The frequency bands defining the frequencies analyzed for each channel were logarithmically equal in width and designed so that adjacent filter bands were -3 dB down at their common edges. The overall range of frequencies analyzed (between outermost -3 dB points) was 350 to 5500 Hz in every case. For the overlapped bands comparison, one side's 11 channels divided the overall range of 395 - 5500 Hz while the other's were adjusted to span 350 - 4879 Hz, causing the band center frequencies on one side to correspond to edges between bands on the other. Finally, for the "Offset-Narrow" bands of processor M7, the width of each of the bands used in the overlapped case was reduced to provide a set of 22 bands contiguous at their -3 dB points.

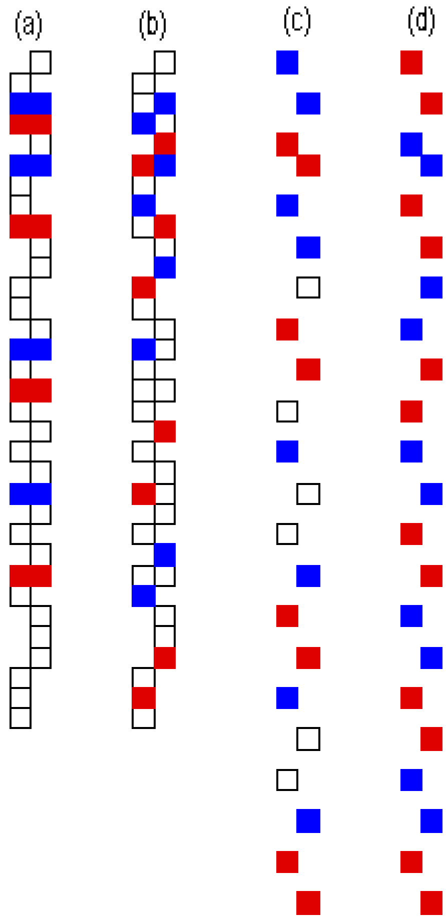

Figure 2. Four assignments of available electrodes to research speech processors. (a) Subject NU-6, eight channel processors using only pitch matched contralateral pairs of electrodes; (b) Subject NU-6, eight channel processors using only pitch distinct contralateral pairs of electrodes; (c) Subject ME-15, eight channel processors using only pitch distinct contralateral pairs of electrodes with no pitch percept overlap between adjacent channels; and (d) Subject ME-15, eleven channel processors using only pitch distinct contralateral pairs of electrodes with no pitch percept overlap between adjacent channels. See Figure 1 above for electrode labels. Squares corresponding to electrodes utilized by each processor design are indicated by shading, with odd and even numbered channels shown as different colors or different shades of gray.

Table I. Processor Parameters

No. of Channels	Pulse Rate, each Channel		Analysis Frequency Bands	
	Synchronous	Asynchronous	Identical	Overlapped
8 (both subjects)	1515 p/s	1515/1510 p/s	350-5500 Hz	
11 (ME-15 only)	1474 p/s	1474/1471 p/s	350-5500 Hz	395-5500/350-4879 Hz

The principal conditions being compared, then, were use of **matched *vs.* unmatched** electrode pairs, use of **synchronous *vs.* asynchronous** processing on the two sides, use of **identical *vs.* overlapping** frequency bands analyzing signals on the two sides, and use of a different **number of channels**. To support these comparisons we produced ten processors, four for subject NU-6 (referred to as N5 - N8 in this report) and six for subject ME-15 (M1, M2, and M4 - M7). The attributes of each are summarized in a four-character code in Table II.

Table II. Configurations for each processor discussed.

Processor Label		Number of Channels	Synch / Asynch	Matched / Unmatched	Identical / Overlapping / Offset-Narrow
NU-6	ME-15				
N5		8	S	M	I
N6	M1	8	S	U	I
N7	M2	8	A	U	I
N8		8	A	M	I
	M4	11	S	U	I
	M5	11	S	U	O
	M6	11	A	U	O
	M7	22	A	U	ON

As these processor designs are referred to in the sections that follow, they will be identified both by the processor label from the first or second column of Table II and by codes corresponding to the rightmost four columns of that table.

Studies

Speech reception in the presence of directionally distinct noise

These studies were done with head-related transfer function (HRTF) processing of speech (from the front) and of CCITT speech spectrum noise (from the right, front, or left -- NR, NF, or NL) combined at various S/N ratios as necessary to achieve test sensitivity. The most thorough evaluation of speech reception in noise involves a total of nine testing conditions, each ear alone and both ears together (RE, BE, LE) for noise incident from each of the three directions. Because of time limitations, some processor comparisons involve only the three BE conditions or even only the BE-NF condition. Speech tests with these subjects included identification of medial consonants in /ah/-C-/ah/ context (using 24 consonants for NU-6 and a subset of 16 consonants appropriate to German for ME-15, with a minimum of 10 presentations of each consonant in each condition), and identification of words in English CUNY sentences (4 lists -- 408 words -- in each condition) or German Oldenburger sentences (40 sentences -- 200 words -- in each condition. Each Oldenburger sentence is formed of five words, one selected randomly from each of five closed lists of personal names, verbs, cardinal numbers, adjectives, and nouns, in that order. The German sentences were scored by a staff member whose first language is German [RS]). Which tests were administered -- and the S/N ratio used -- are indicated for each condition discussed below.

Synchronous vs. Asynchronous comparisons

Our studies included four comparisons of processors differing only in whether the two sides were stimulated synchronously (*i.e.* simultaneously) or asynchronously (*i.e.* with a small rate difference). The conditions may be summarized in Table III.

Speech reception data will be shown side-by-side -- with the synchronous case on the left -- for each of those conditions. The scale at the left of each panel will indicate 0 - 100% correct identification. In every case striped bars (black) will indicate performance with use of both processors and with noise from the right, the front, and the left, and solid (red) bars will indicate the degree of binaural benefit when the noise direction is distinct. When data from all nine combinations of noise direction and processor configuration are available, solid bars in the upper panels also will indicate the degree to which various mechanisms -- head shadow (black), binaural summation (green), and squelch (orange) -- contribute to performance, and additional panels below will indicate binaural advantage with spatial separation as solid (green) bars. Both types of display were introduced and discussed in detail in QPR 12 for the previous contract (N01-DC-8-2105). In the HTML version of this report, many smaller nine-combination plots are "hot," so that a mouse clicked while its cursor is on one of a pair of small plots will cause a large version of that plot to be displayed in a separate window, after which the reader may click on the browser's "Back" button to resume reading the report. Percent correct values plotted in Figures 3 - 8 are displayed numerically in Table IV below, along with uncertainties for each condition in terms of standard deviation of the mean. Table IV also includes data for some additional, related conditions, such as additional S/N ratios.

Table III. Synchronous *vs.* asynchronous stimulation comparisons

Processors Compared		Other Characteristics			S/N for Consonants		S/N for Sentences	
Synch.	Asynch.				RE,BE, LE	BE Only	RE,BE, LE	BE Only
N5	N8	8	M	I	0	+5	+5	
N6	N7	8	U	I	0	+5		+5
M1	M2	8	U	I		-5, 0		
M5	M6	11	U	O	-5			
M4		11	U	I				0

Figures 3 and 4 show data for NU-6 comparing the same pair of processors, but with different speech materials and at different S/N ratios. While the asynchronous case supports clearly superior performance with the CUNY sentences at +5 dB, the synchronous version does slightly better (at least for BE, NR) with consonants at 0 dB.

N5 *vs.* N8; +5 dB S/N; words in CUNY sentences

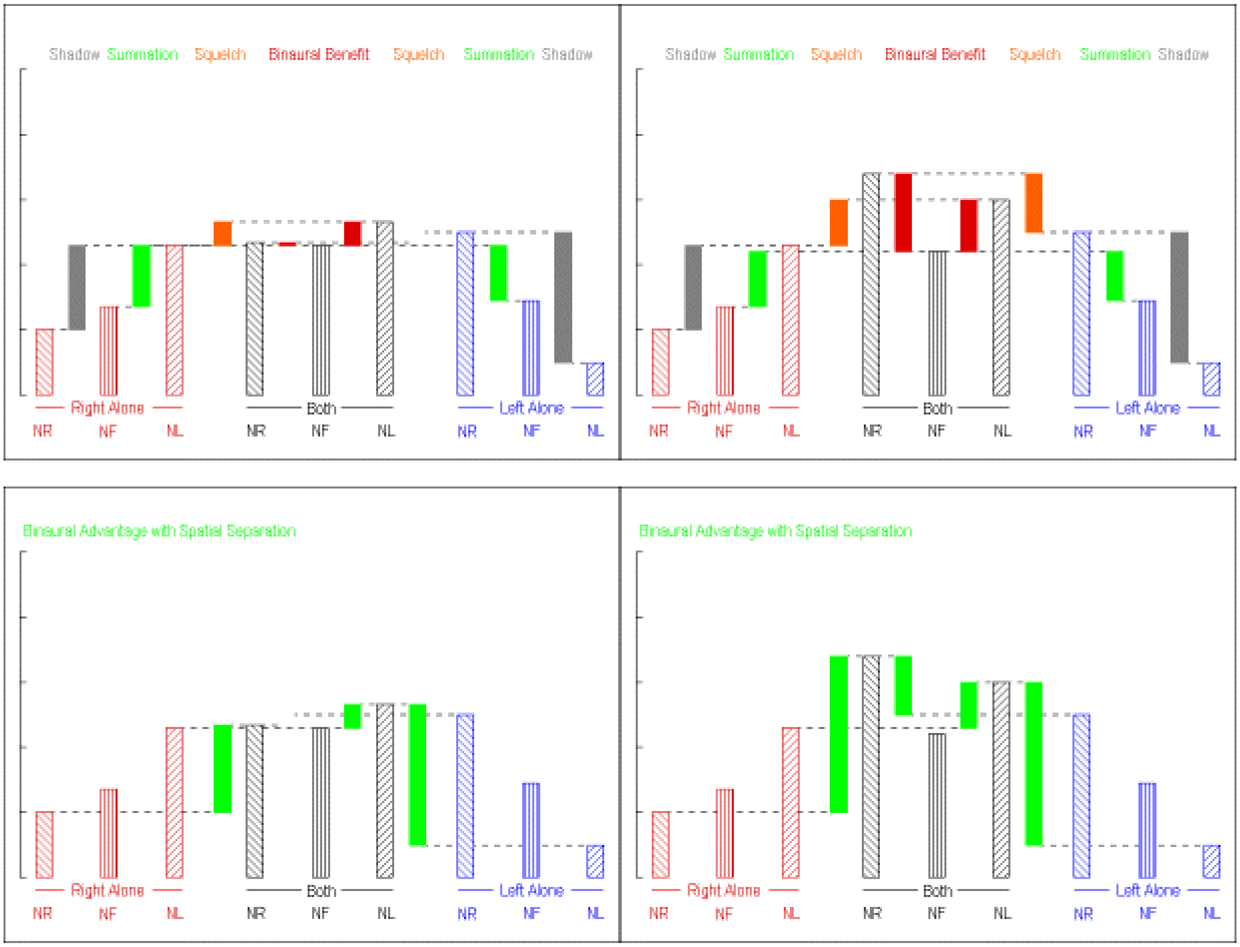

Figure 3. Subject NU-6: Identification of words in CUNY sentences presented at a S/N of +5 dB, with synchronous (left column) and asynchronous (right column) processors on the two sides. In both cases, 8 channel processors were used to stimulate pitch matched pairs of contralateral electrodes. The frequency bands used for analysis were identical on the two sides. Solid bars indicate the magnitude of binaural benefit and its components in the upper panels, and binaural advantage with spatial separation in the lower panels.

N5 *vs.* N8; 0 dB S/N; 24 consonants

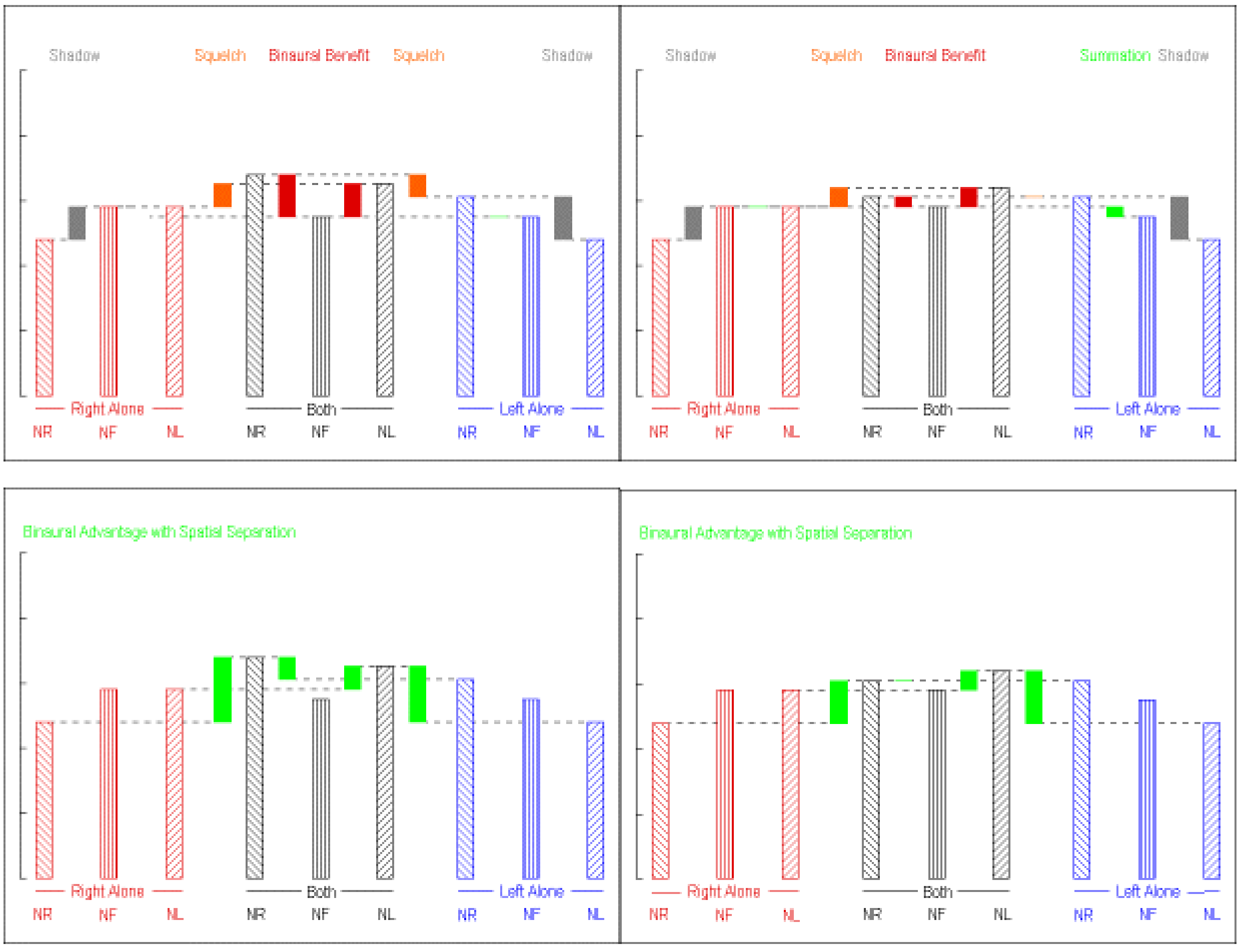

Figure 4. Subject NU-6: Identification of 24 medial consonant tokens presented at a S/N of 0 dB, with synchronous (left column) and asynchronous (right column) processors on the two sides. In both cases, 8 channel processors were used to stimulate pitch matched pairs of contralateral electrodes. The frequency bands used for analysis were identical on the two sides. Solid bars indicate the magnitude of binaural benefit and its components in the upper panels, and binaural advantage with spatial separation in the lower panels.

When the same comparison was made using similar processors but unmatched pairs of electrodes (Figure 5), the consonant results showed no significant difference between synchronous and asynchronous conditions.

N6 *vs.* N7; 0 dB S/N; 24 consonants

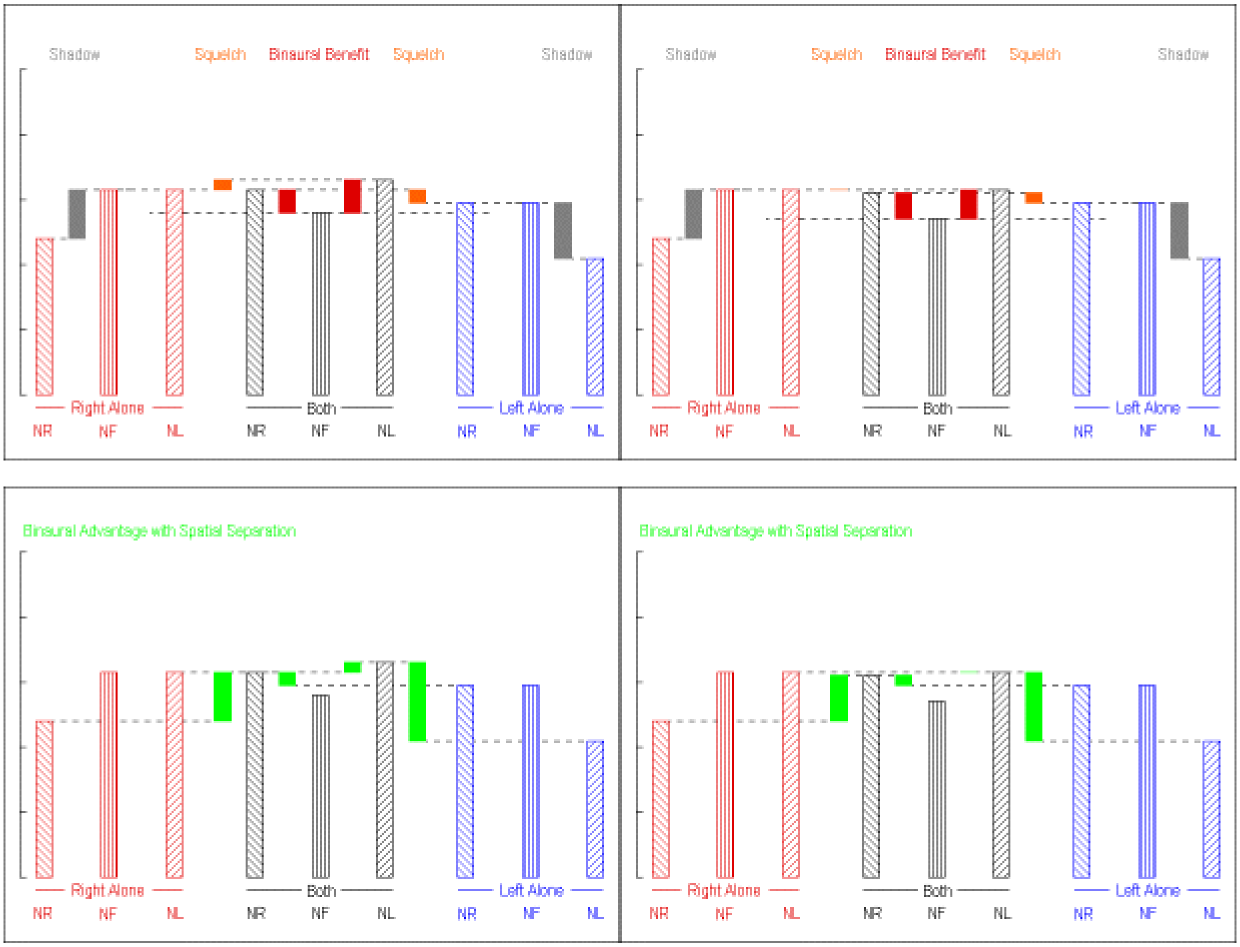

Figure 5. Subject NU-6: Identification of 24 medial consonant tokens presented at a S/N of 0 dB, with synchronous (left column) and asynchronous (right column) processors on the two sides. In both cases, 8 channel processors were used to stimulate pitch distinct pairs of contralateral electrodes. The frequency bands used for analysis were identical on the two sides. Solid bars indicate the magnitude of binaural benefit and its components in the upper panels, and binaural advantage with spatial separation in the lower panels.

In Figure 6 we switch to data for ME-15 using a similar pair of processors with unmatched electrode pairs. While the difference in the NF condition between the two cases is not significant, the BE, NR performance is significantly better with the synchronous processors, as is overall binaural benefit.

M1 *vs.* M2; -5 dB S/N; 16 consonants

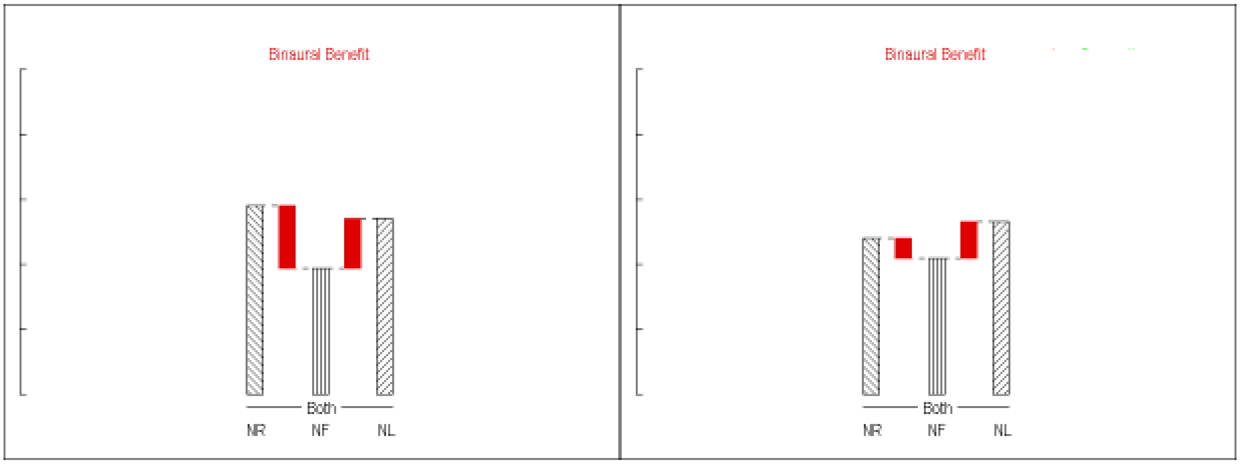

Figure 6. Subject ME-15: Identification of 16 medial consonant tokens presented at a S/N of -5 dB, with synchronous (left panel) and asynchronous (right panel) processors on the two sides. In both cases, 8 channel processors were used to stimulate pitch distinct pairs of contralateral electrodes. The frequency bands used for analysis were identical on the two sides. Solid bars indicate the magnitude of binaural benefit.

A comparison with 11 channel processors in Figure 7 doesn't reveal a significant difference in overall performance, but the asynchronous case appears to be better balanced between the two ears.

In Figure 8 we include some sentence data for a related 11 channel processor indicating relatively large binaural benefits, especially for the NR condition. Similar data taken for processor M6 are included in Table IV, but have not been plotted here with M4 because of the difference in analysis frequency bands. In that case, binaural benefits are almost as great overall but, in contrast, notably better in the NL condition.

M5 *vs.* M6; -5 dB S/N; 16 consonants

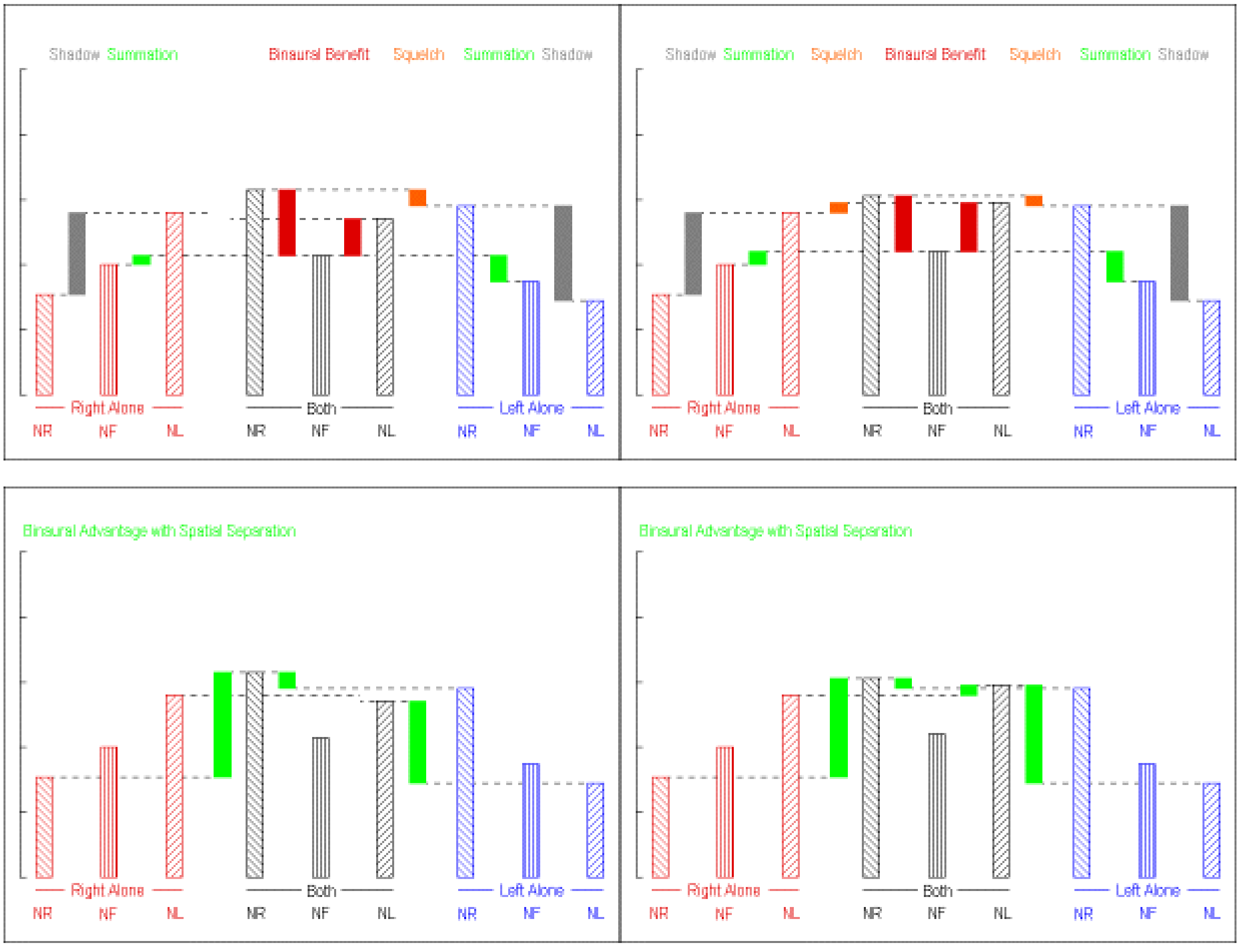

Figure 7. Subject ME-15: Identification of 16 medial consonant tokens presented at a S/N of -5 dB, with synchronous (left column) and asynchronous (right column) processors on the two sides. In both cases, 11 channel processors were used to stimulate pitch distinct pairs of contralateral electrodes. The frequency bands used for analysis on the two sides were overlapped. Solid bars indicate the magnitude of binaural benefit and its components in the upper panels, and binaural advantage with spatial separation in the lower panels.

M4; 0 dB S/N, words in Oldenburger sentences

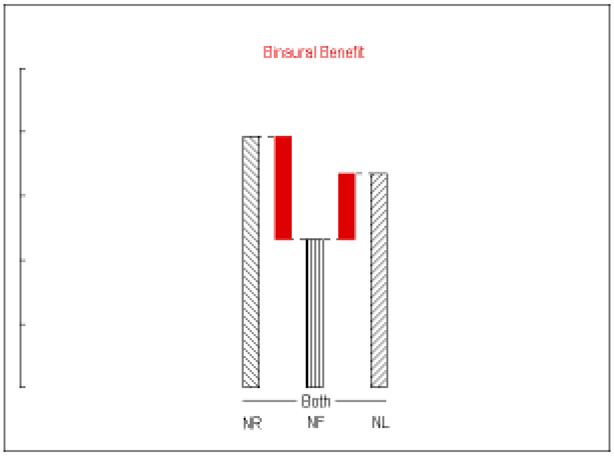

Figure 8. Subject ME-15: Identification of words in Oldenburger sentences presented at a S/N of 0 dB, with synchronous processors on the two sides. 11 channel processors were used to stimulate pitch distinct pairs of contralateral electrodes. The frequency bands used for analysis were identical on the two sides. Solid bars indicate the magnitude of binaural benefits.

In summary, while significant performance differences between asynchronous and synchronous versions of otherwise identical processors can be found, there does not appear to be any systematic advantage to difficult-to-achieve synchronous processing. These results are consistent with findings across all our bilaterally implanted subjects.

Table IV. Synchronous *vs.* asynchronous percent correct data with statistical uncertainties (standard deviation of the mean)

Proc.	S/A	M/U	RE			BE			LE		
			NR	NF	NL	NR	NF	NL	NR	NF	NL
+5 dB, CUNY sentences											
N5	S	M	20±4	27±4	46±5	47±10	46±7	53±8	50±5	29±8	10±2
N8	A	M	20±4	27±4	46±5	68±3	44±5	60±0	50±5	29±8	10±2
N6	S	U				58±3	44±3	49±5			
N7	A	U				80±5	47±4	63±3			

Table IV. *continued*

0 dB, 24 consonants											
N5	S	M	48±3	58±3	58±2	68±2	55±2	65±2	61±3	55±2	48±2
N8	A	M	48±3	58±3	58±2	61±2	58±2	64±2	61±3	55±2	48±2
N6	S	U	48±2	63±3	63±2	63±3	56±2	66±3	59±2	59±3	42±4
N7	A	U	48±2	63±3	63±2	62±2	54±2	63±2	59±2	59±3	42±4
+5 dB, 24 consonants											
N5	S	M					64±2				
N8	A	M					69±3				
N6	S	U					63±2				
N7	A	U					67±4				
Quiet, 24 consonants											
N5	S	M					76±2				
N8	A	M					82±2				
N6	S	U					78±3				
N7	A	U					85±3				
-5 dB, 16 consonants											
M1	S	U				58±3	39±3	54±3			
M2	A	U				48±3	42±2	53±4			
M5	S	U	31±3	40±4	56±5	63±2	43±5	54±3	58±2	35±2	29±3
M6	A	U	31±3	40±4	56±5	61±3	44±2	59±3	58±2	35±2	29±3
0 dB, Oldenburger sentences											
M4	S	U				79±2	47±5	67±3			
M6	A	U				71±3	55±2	78±3			

Pitch matched vs. Unmatched electrode pair comparisons

As mentioned above, the pattern of pitch ranking among subject NU-6's electrodes supported comparisons of 8 channel processors differing only in whether the contralateral electrode pair assigned to each channel involved pitch matched or pitch distinct electrodes. Two comparisons were available, one with synchronous processing and the other with asynchronous, as summarized in Table V.

Table V. Matched *vs.* unmatched electrode comparisons

Processors Compared		Other Characteristics			S/N for Cons.	
Matched	Unmatched				RE,BE,LE	BE Only
N5	N6	8	S	I	0	+5
N8	N7	8	A	I	0	+5

The data are displayed in bar chart form in Figures 9 and 10, with pitch matched electrode processors in the left column and pitch distinct electrode processors in the right column. The same data also are available in numeric form with indications of statistical uncertainty in Table VI, along with additional performance data for the same processors in quiet and at a S/N of +5 dB.

There is no evidence of any significant performance advantage to pitch matched or pitch distinct (unmatched) electrodes in these processors for which the analysis bands are identical on the two sides.

N5 *vs.* N6; 0 dB S/N; 24 consonants

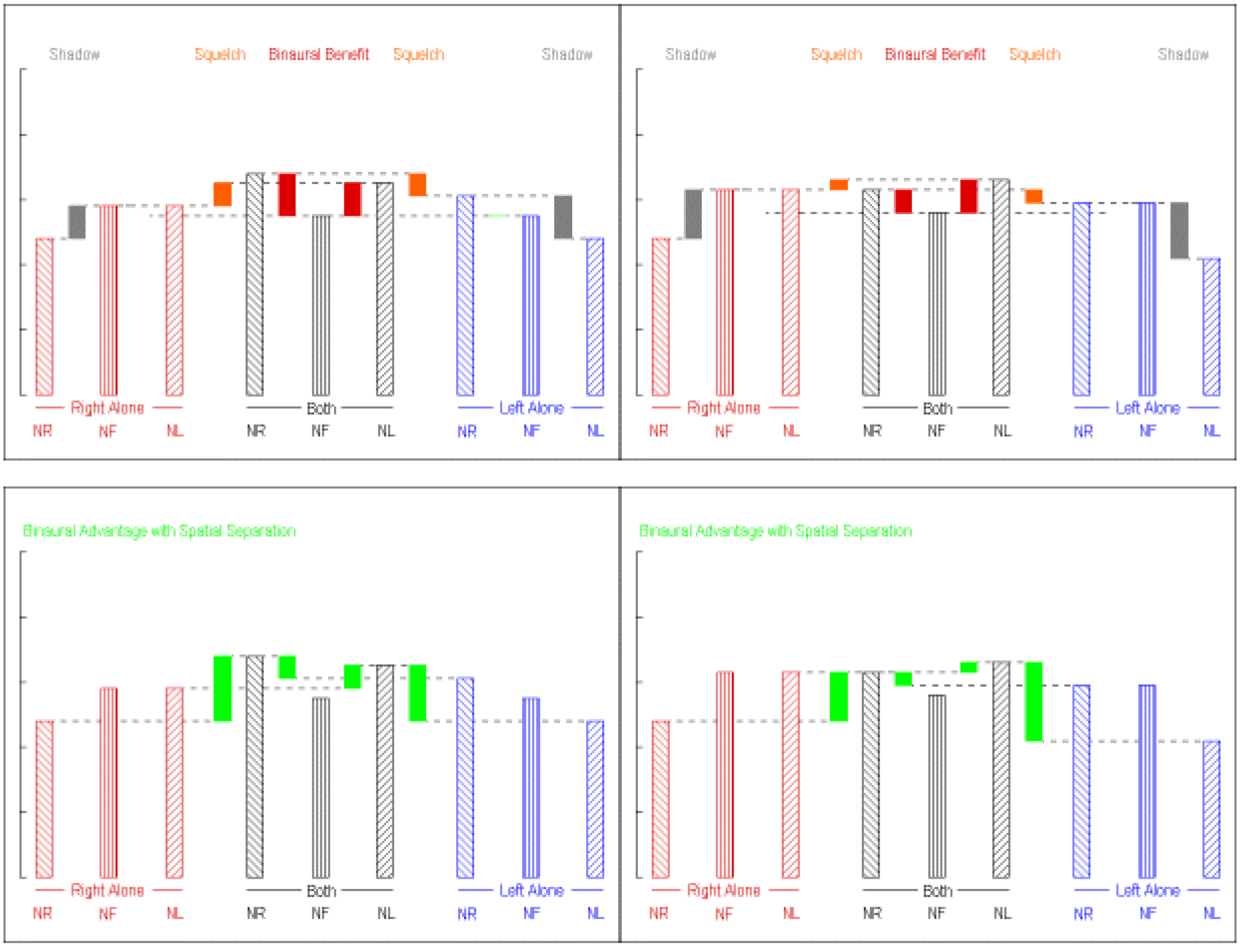

Figure 9. Subject NU-6: Identification of 24 medial consonant tokens presented at a S/N of 0 dB, with pitch matched (left column) and pitch distinct (right column) processors on the two sides. In both cases, synchronous 8 channel processors were used. The analysis frequency bands used were identical on the two sides. Solid bars indicate the magnitude of binaural benefit and its components in the upper panels, and binaural advantage with spatial separation in the lower panels.

N8 *vs.* N7; 0 dB S/N; 24 consonants

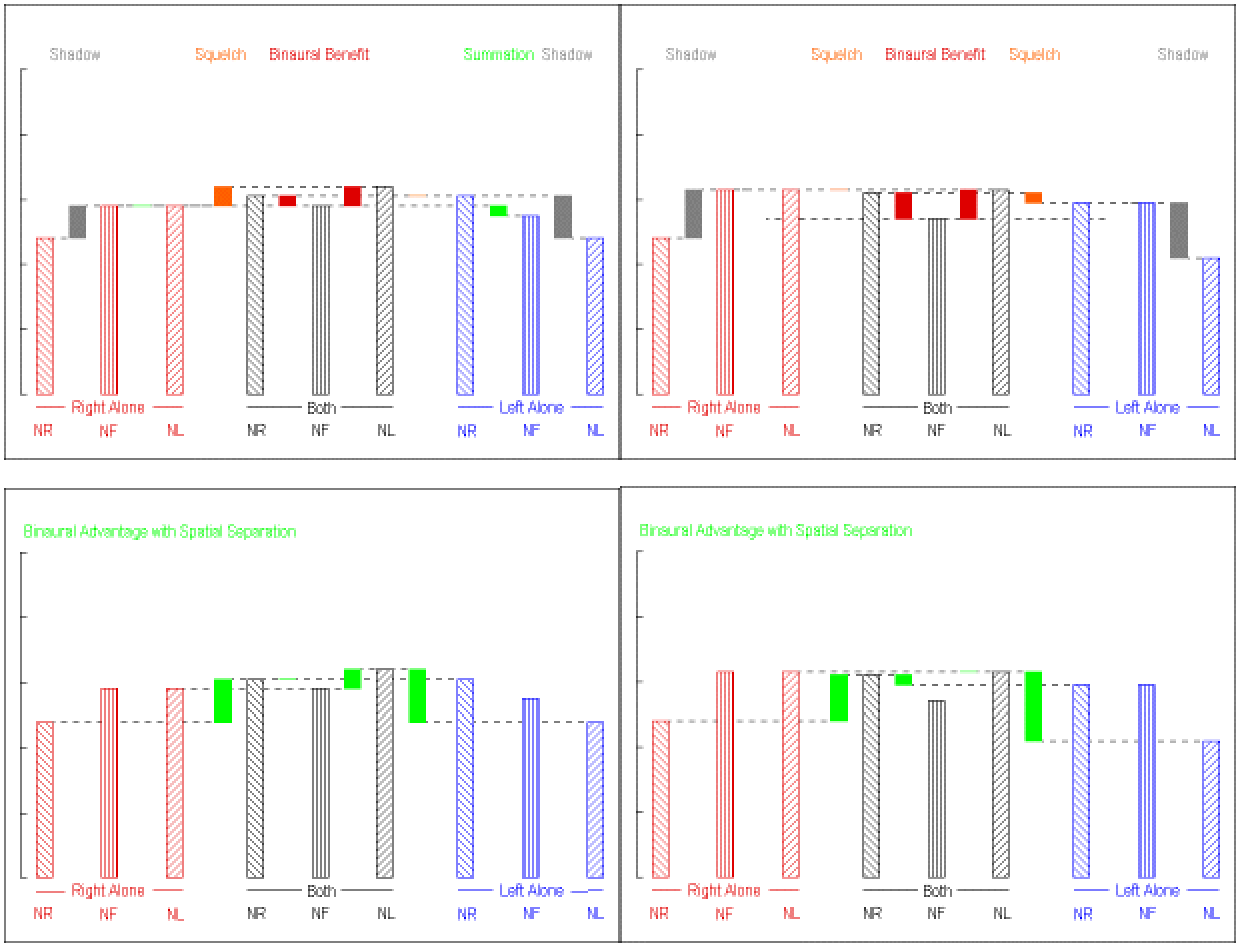

Figure 10. Subject NU-6: Identification of 24 medial consonant tokens presented at a S/N of 0 dB, with pitch matched (left column) and pitch distinct (right column) processors on the two sides. In both cases, asynchronous 8 channel processors were used. The analysis frequency bands used were identical on the two sides. Solid bars indicate the magnitude of binaural benefit and its components in the upper panels, and binaural advantage with spatial separation in the lower panels.

Table VI. Matched *vs.* unmatched percent correct data with statistical uncertainties (standard deviation of the mean)

Proc.	M/U	S/A	RE			BE			LE		
			NR	NF	NL	NR	NF	NL	NR	NF	NL
0 dB, 24 consonants											
N5	M	S	48±3	58±3	58±2	68±2	55±2	65±2	61±3	55±2	48±2
N6	U	S	48±2	63±3	63±2	63±3	56±2	66±3	59±2	59±3	42±4
N8	M	A	48±3	58±3	58±2	61±2	58±2	64±3	61±3	55±2	48±2
N7	U	A	48±2	63±3	63±2	62±2	54±2	63±2	59±2	59±3	42±4
+5 dB, 24 consonants											
N5	M	S					64±2				
N6	U	S					63±2				
N8	M	A					69±3				
N7	U	A					67±4				
Quiet, 24 consonants											
N5	M	S					76±2				
N6	U	S					78±2				
N8	M	A					82±2				
N7	U	A					85±3				

Identical vs. Overlapping analysis band comparison

When identical frequency analysis bands are used on both sides for binaural processing, the borders between adjacent bands occur at the same frequencies for both sides. At those frequencies, any input is represented equally in two channels, whereas for frequencies near the middle of some band the representation would be confined to a single channel. These considerations led us to compare identical sets of 11 analysis bands with an alternative arrangement. In this alternative, the bands on one side are shifted slightly to higher frequencies and those on the other to slightly lower frequencies, so that (1) the overall frequency range analyzed remains 350 - 5500 Hz, and (2) the borders between adjacent bands on one side occur at the same frequencies as the band centers on the other side. The borders between adjacent bands occur at common -3 dB points on both sides in both designs. The specific frequencies for the overlapping bands may be found in the left half of Table IX below.

The designs are summarized in Table VII. The comparison data are displayed graphically in Figure 11 and included in a numerical summary with indications of statistical uncertainties in Table XI.

Table VII. Identical *vs.* overlapping analysis band comparison

Processors Compared		Other Characteristics			S/N for Cons.
Identical	Overlapping				RE,BE,LE
M4	M5	11	S	U	-5

M4 *vs.* M5; -5 dB S/N; 16 consonants

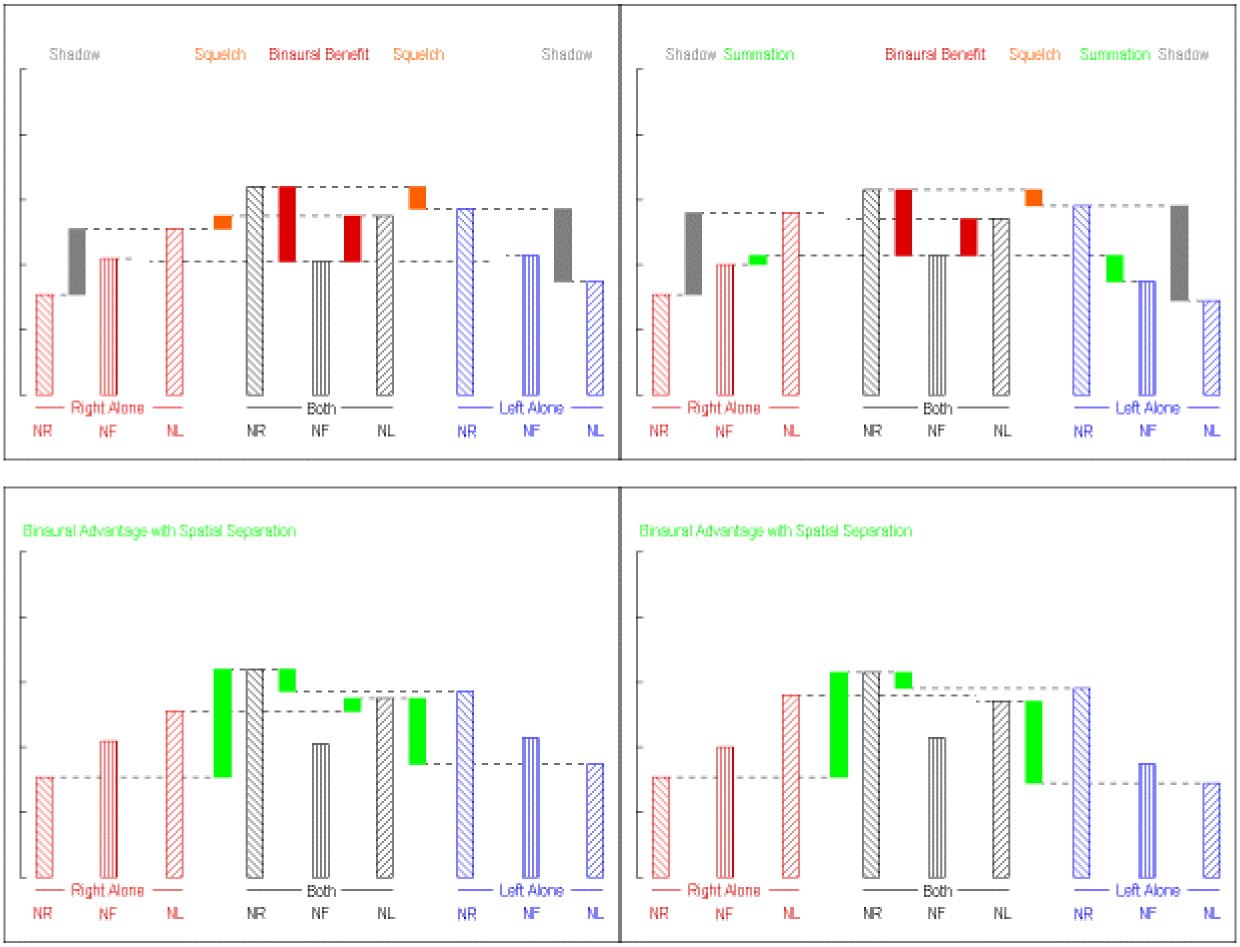

Figure 11. Subject ME-15: Identification of 16 medial consonant tokens presented at a S/N of -5 dB, with identical analysis bands on the two sides (left column) and overlapped analysis bands whose centers on one side correspond to the borders between bands on the other (right column). In both cases, synchronous 11 channel processors were used. Solid bars indicate the magnitude of binaural benefit and its components in the upper panels, and binaural advantage with spatial separation in the lower panels.

We find no significant difference in performance of 11 channel synchronous processors on a medial consonant identification task between identical and overlapping frequency analysis bands.

11 vs. 22 Channel comparison: Overlapping vs. Offset Distinct Bands

If separate sets of frequency analysis bands are to be used on the two sides for a binaural pair of 11 channel processors, another option is to distribute between them a set of 22 non-overlapping bands, leaving spectral gaps between adjacent bands on each side corresponding to bands analyzed on the other side. We have compared such a strategy with asynchronous processors, one using the same overlapping stereophonic sets of 11 bands used in M5 and the other using a single set of 22 non-overlapping bands, also stereophonically. The processors are described in Table VIII, and the specific frequency analysis bands in Table IX. Consonant and sentence data are displayed as bar charts in Figures 12 and 13, respectively, and included among the numeric data with statistical uncertainties in Table XI.

Table VIII. Eleven *vs.* twenty-two channel comparison

Processors Compared		Other Characteristics		S/N	
11/11 Chan.	22 Chan.			Cons.	Sent.
Overlapped Bands	Distinct Bands			BE Only	BE Only
M6	M7	A	U	-5	0

Table IX. Overlapped *vs.* Distinct Frequency Bands

2 x 11 channels Overlapped Bands		22 channels Distinct Bands	
lf side	hf side	lf side	hf side
350-445 Hz	395-501 Hz	350-397 Hz	397-450 Hz
445-565	501-637	450-510	510-578
565-718	637-809	578-655	655-742
718-912	809-1028	742-841	841-953
912-1159	1028-1307	953-1080	1080-1224
1159-1473	1307-1660	1224-1387	1387-1573
1473-1872	1660-2110	1573-1782	1782-2020
1872-2378	2110-2681	2020-2289	2289-2595
2378-3022	2681-3407	2595-2941	2941-3333
3022-3840	3407-4328	3333-3778	3778-4282
3840-4879	4328-5500	4282-4853	4853-5500

For identification of consonants, the slightly better performance with the overlapped bands in the NL condition is not significant. NF performance is significantly better with the non-overlapping bands.

M6 *vs.* M7; -5 dB S/N; 16 consonants

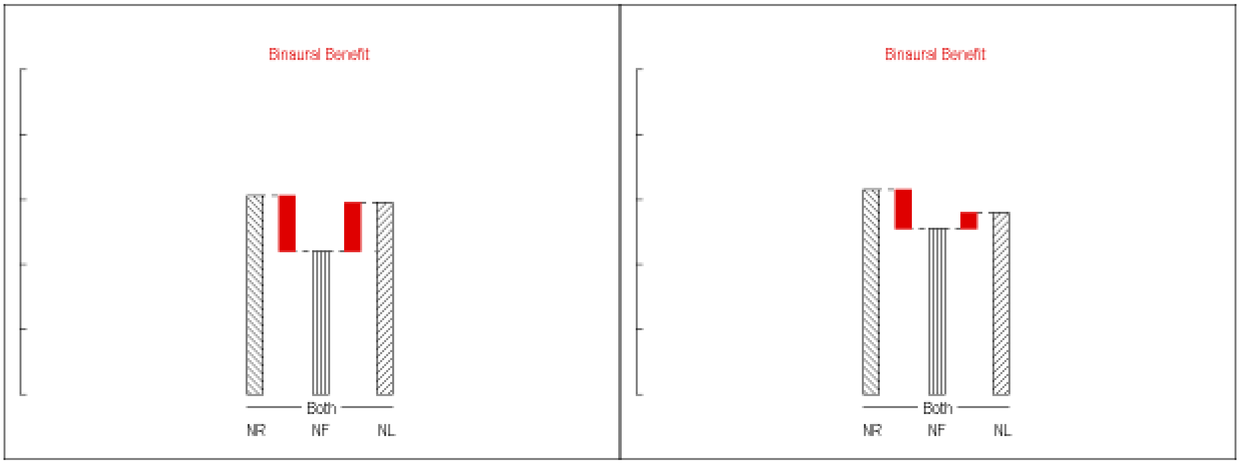

Figure 12. Subject ME-15: Identification of 16 medial consonant tokens presented at a S/N of -5 dB, with overlapped analysis bands whose centers on one side correspond to the borders between bands on the other (left panel) and narrower, non-overlapping analysis bands with the same center frequencies (right panel) In both cases, asynchronous 11 channel processors were used. Solid bars indicate the magnitude of binaural benefit.

M6 *vs.* M7; 0 dB S/N; Oldenburger sentences

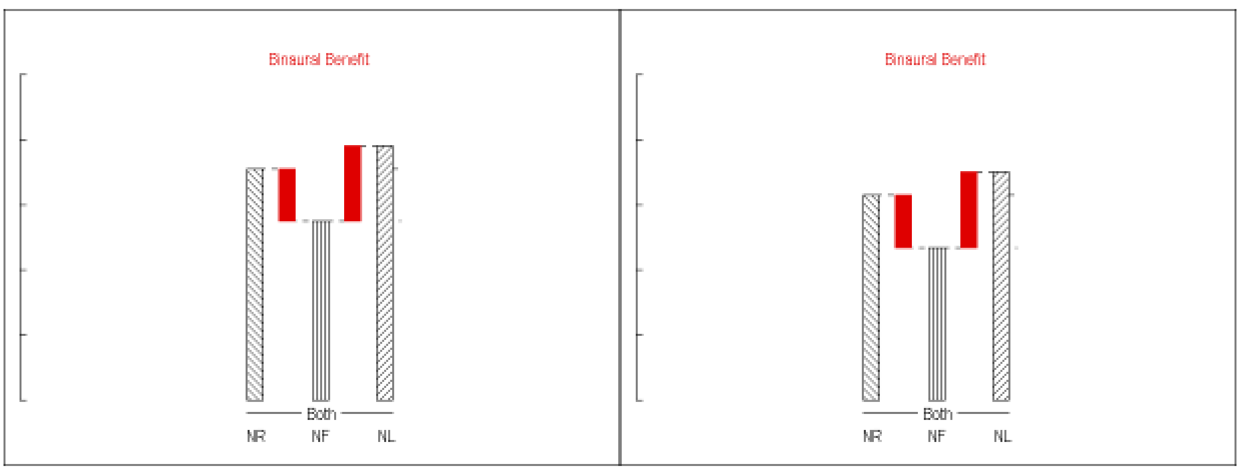

Figure 13. Subject ME-15: Identification of words in Oldenburger sentences presented at a S/N of 0 dB, with overlapped analysis bands whose centers on one side correspond to the borders between bands on the other (left panel) and narrower, non-overlapping analysis bands with the same center frequencies (right panel) In both cases, asynchronous 11 channel processors were used. Solid bars indicate the magnitude of binaural benefit.

For words in Oldenburger sentences, performance is significantly poorer in both NR and NL conditions when the 22 distinct non-overlapping analysis bands are used. (An unusually large uncertainty in data for the NF condition with processor M7 deprives the difference in that condition of any significance.)

Since -- at least for medial consonant identification -- performance with the overlapping bands is not significantly different from that with identical analysis bands on the two sides (see comparison of M4 and M5, Figure 11 above), the additional processor complexity of having different bands does not seem to be justified. Of course, the difference seen with sentence materials in Figure 13 was not evident with consonant identification in Figure 12. The closest comparison we have using sentence materials was included at the bottom of Table IV, between processors M4 and M6. Those processors differ in synchronicity as well as analysis band design, however, and support very similar levels of performance except that the binaural benefit is greater for NR than NL in the case of processor M4.

An approximate simulation of our laboratory overlapping bands design was programmed into NU-6's clinical BTE processors. Her anecdotal reports after several weeks' experience with those processors indicate that the overlapping design may offer advantages for listening to music. We plan follow-up studies regarding that possibility.

8 vs. 11 Channel comparison

Our data also provide one comparison of two processors that are very well matched in all respects except number of channels. The designs are outlined in Table X and the data displayed, as in our other comparisons, in Figure 14 and Table XI.

Table X. Eight *vs.* eleven channel comparison

Processors Compared		Other Characteristics			S/N for Cons.
8 Chan.	11 Chan.				BE Only
M1	M4	S	U	I	-5

M1 *vs.* M4; -5 dB S/N; 16 consonants

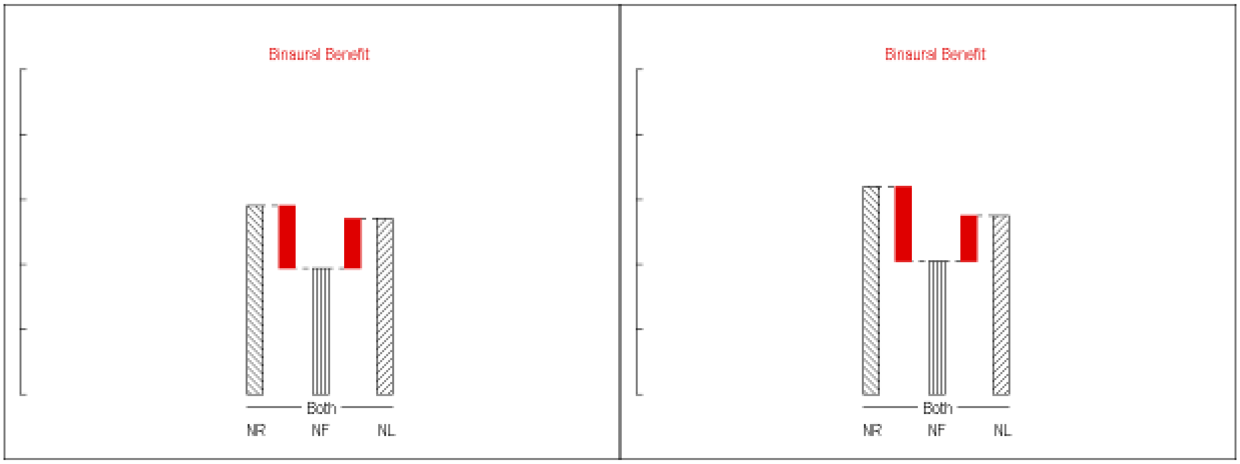

Figure 14. Subject ME-15: Identification of 16 medial consonant tokens presented at a S/N of -5 dB, with bilateral 8 channel processors (left panel) and bilateral 11 channel processors (right panel). In both cases, synchronous processors were used, with pitch distinct (unmatched) electrode pairs assigned to each channel. Solid bars indicate the magnitude of binaural benefit.

In the NR condition, the 11 channel processors support significantly better medial consonant identification than the 8 channel ones.

Table XI. Analysis band and channel number percent correct data with statistical uncertainties (standard deviation of the mean)

Proc.	I/O/ON	Chans.	RE			BE			LE		
			NR	NF	NL	NR	NF	NL	NR	NF	NL
-5 dB, 16 consonants											
M4	I	11	31±3	42±2	51±4	64±2	41±4	55±4	57±4	43±3	35±3
M5	O	11	31±3	40±4	56±5	63±2	43±5	54±3	58±2	35±2	29±3
M1	I	8				58±3	39±3	54±3			
M4	I	11	31±3	42±2	51±4	64±2	41±4	55±4	57±4	43±3	35±3

Table XI. *continued*

M6	O	11	31±3	40±4	56±5	61±3	44±2	59±3	58±2	35±2	29±3
M7	ON	22				63±3	51±3	56±3			
0 dB, Oldenburger sentences											
M6	O	11				71±3	55±2	78±3			
M7	ON	22				63±4	47±7	70±4			

Another perspective on the various performance comparisons conducted with subject ME-15 is provided in Figure 15, where we have plotted BE NR, NF,and NL consonant identification scores at -5 dB S/N. From left to right, the bars in each group represent processors M4, M5, M6, M7 and the subject's clinical Tempo+ processors tested using his custom in-the-canal microphone system (see below) under headphones. Error bars indicate standard deviation of the mean. The most striking aspect of these data is the consistency of performance across a variety of design manipulations. The only significant differences are (1) that -- at least under headphones -- the clinical arrangement performs significantly less well than any of the research processors for NR and NF, and (2) that M7 performs significantly better than any of the others for the NF condition. With 8 or 11 channels on each side, and with electrodes chosen from sets with very consistent patterns of pitch ranking, these two subjects' generally high levels of performance are remarkably insensitive to a variety of processor design variations.

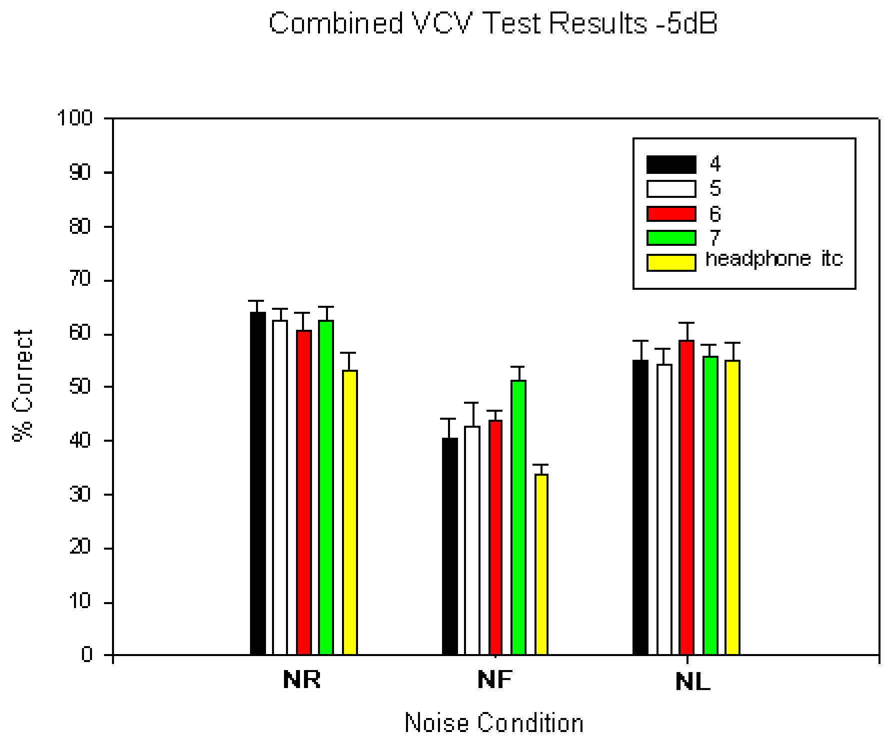

Figure 15. Subject ME-15: Identification of 16 medial consonant tokens presented at a S/N of -5 dB, for processors M4, M5, M6, M7, and the subject's clinical devices used with his custom in-the-canal microphone system and headphones.

Lateralization on the basis of interaural differences

Subject NU-6 offered a total of eight pitch matched contralateral pairs of electrodes, four of which were utilized in measurements of the minimum IAD and ITD values required for reliable lateralization. Pulse trains at two different rates were used -- 100 and 2400 p/s. The results are summarized in Table XI.

Table XII. Summary of IAD ITD data for NU-6: percent correct for lateralization to the louder side, and ITD in μs.

	Percent correct IAD lateralization														ITD	
Electrodes	100 p/s							2400 p/s								
	10 CU	8	6	4	3	2	1	10 CU	8	6	4	3	2	1	100 p/s	2400 p/s
L17-R18					100%	100	100								101μs	487μs
L10-R11					100	100	90					100%	50	50		
L4-R5					100	100	50								127	93
L2-R2	100%	85	85	50								100	100	88		

The IAD studies utilized simultaneous pulse trains to the two sides, with IAD measured in terms of the difference in clinical units (CU) with respect to a loudness balanced condition. (1 CU is the minimum amplitude change available from the implanted device.) For electrode pair L2 - R2, NU-6 required an IAD of 6 CU or more for lateralization when the stimulus rate was 100 p/s, but only 2 CU when a rate of 2400 p/s was used. For all other tested combinations of pitch matched electrode pair and pulse rate, lateralization was achieved with differences of only 1 to 3 CU.

Our ITD measurements utilized temporally offset pulse bursts at loudness balanced amplitudes. The ITD value was determined as the point at which a logistic fit of percent lateralization to the earlier signal as a function of delay equaled 75%. [This method was described in QPR 12 for our previous contract N01-DC-8-2105.]

In three of the four tested combinations of pair and rate, the minimum ITD needed for lateralization by NU-6 was approximately 100μs, while use of the higher rate for electrode pair L17 - R18 required a delay of almost 500μs.

Thus, while we have observed substantial variations in IAD and ITD with differences in pulse rate, no simple pattern of dependence has emerged.

Both subjects took part in studies of lateralization on the basis of ITD in which the electrode location was fixed on one side, near the middle of the array, and varied along the array on the other side. For NU-6 the fixed electrode was L10, and the function of ITD *vs.* contralateral electrode position was found to have a minimum for positions near R10. The rise in the function was more gradual toward the apical end of the array. The electrode pair L10 - R11 was one of those identified as pitch matched.

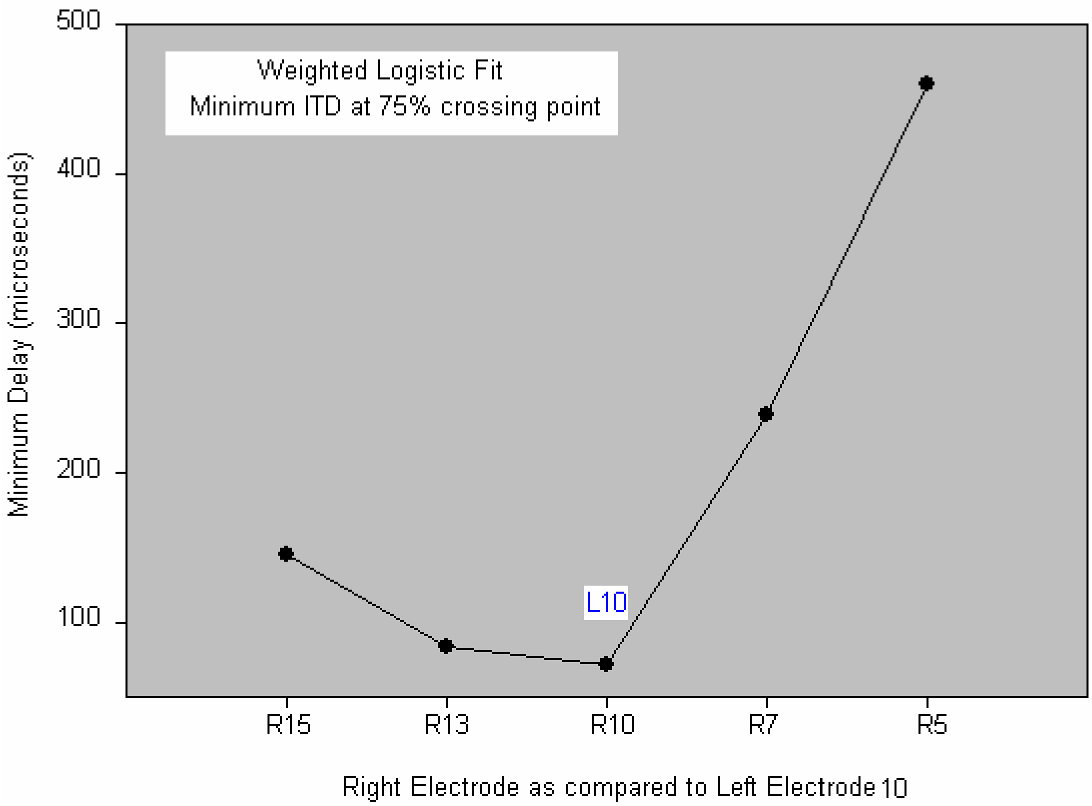

Figure 16. Subject NU-6: Minimum interaural time delay required for lateralization of loudness balanced pulse trains, as a function of position of right side electrode with respect to a fixed left side electrode.

For subject ME-15 the fixed electrode chosen was L7, and a minimum in the function was found for right side electrode locations in the R5 to R7 region. The function displays an asymmetry similar to that found for NU-6, with a more gradual increase in the apical direction. The large difference between the ITDs observed for R8 and R9, however, make it difficult to assess the degree of similarity.

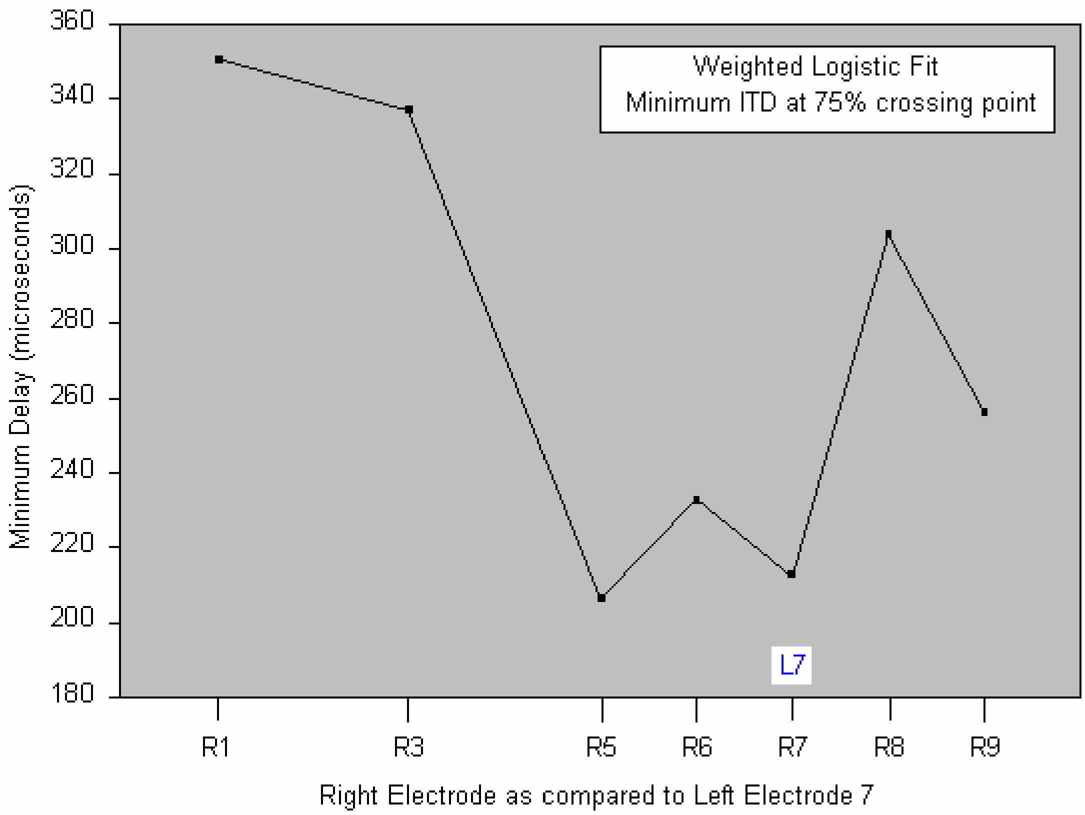

Figure 17. Subject ME-15: Minimum interaural time delay required for lateralization of loudness balanced pulse trains, as a function of position of right side electrode with respect to a fixed left side electrode.

Subject ME-15's custom ITC microphone system

As noted in the discussion of subjects above, ME-15 has assembled a custom system that provides him the option of using ITC microphones rather than the ones mounted in his standard Tempo+ devices, and to mix those signals and/or inductive loop signals from assistive devices before injecting them into his Tempo+ electronics for processing and cochlear stimulation. Microphone cables run from his ITC microphone inserts to a thin custom electronics unit suspended over his chest by a neck strap, and cables carrying the outputs of that unit run back up to the auxiliary inputs of his Tempo+ BTE packages. Both sets of cables are dressed along the unit's neck strap to convenient locations on either side of the neck, from which they extend upward to the ears and associated Tempo+ BTE units.

The subject was motivated to develop such a system by the severe impact of wind noise on speech understanding in two particular situations -- downhill skiing and standing watch on the deck of a sailing vessel. As he reported large benefits from the use of his custom system in noisy situations, we arranged to compare his speech reception performance in a free field situation, using an audiological suite at Duke University Medical Center.

ME-15's Tempo+ processors, running his everyday processing programs, were used with each set of microphones. Two calibrated loudspeaker units were displaced 90 degrees from each other at a radius of 3 ft. with respect to the subject's location. Speech was fed from the loudspeaker the subject was facing in every case, with noise coming also from the front (mixed to the same loudspeaker using an audiometer), or from 90 degrees to the right or left. Identification of words in the Oldenburger formulaic sentences was measured for 40 sentences (200 words) in each condition, with both speech and noise channels at 65 dB-A. Occasional SPL peaks observed during speech were < 3 dB above noise when measured at the subject's chair, regardless of source locations. Scoring was by a staff member whose first language is German [RS]. The results are shown in Figure 18 and Table XIII.

Standard mastoid microphones *vs.* custom in-the-canal microphone system

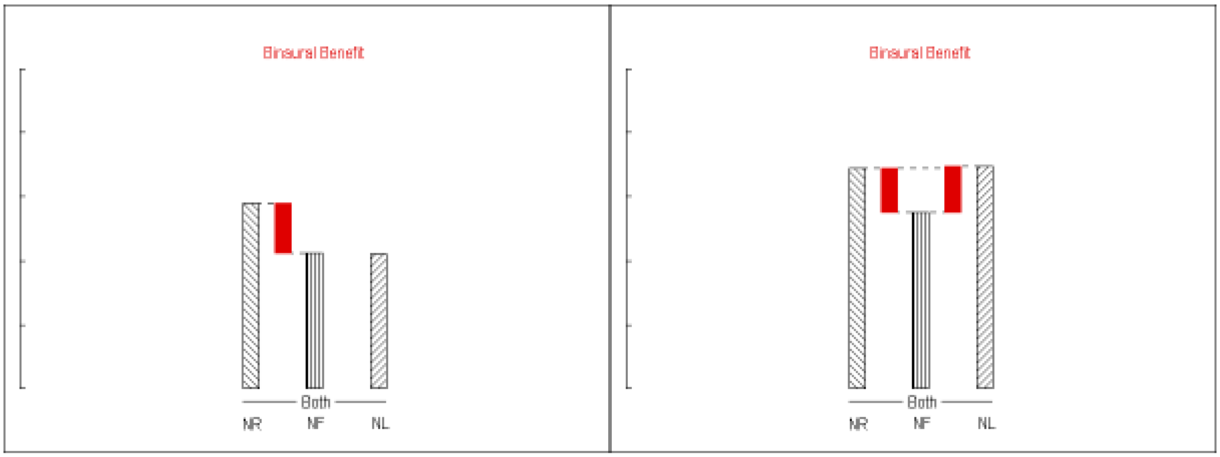

Figure 18. Subject ME-15: Identification of words in Oldenburger sentences presented at a S/N of 0 dB at 65 dB-A in free field, with standard clinical microphones (left panel) and this subject's custom in-the-canal microphone system (right panel). In both cases, the subject's everyday Tempo+ clinical processors were used. Solid bars indicate the magnitude of binaural benefit.

The results supported the subject's anecdotal reports. Both NF and NL conditions show significantly better performance with the ITC system.

Table XIII. BTE *vs.* ITC microphone percent correct data with uncertainties.

Proc.	Mic.		RE			BE			LE		
			NR	NF	NL	NR	NF	NL	NR	NF	NL
dB, Oldenburger sentences											
Tempo	BTE					58±7	43±8	42±3			
Tempo	ITC					69±5	55±3	70±2			

Summary

For two subjects with different implanted devices and very different pitch ranking patterns among their bilateral electrodes -- but both with generally quite good levels of speech reception performance -- we have observed substantial binaural benefit (and binaural advantage when speech and noise directions are distinct) for a variety of processor designs with 8 or more channels per side. Neither variations in stimulation synchronicity, nor analysis band overlap or offset, nor pitch matching or pitch distinct assignments of electrodes to channels, had any significant systematic effect on performance in noise.

For both subjects, minima were observed in the minimum interaural time delay (ITD) required for lateralization, as a function of electrode location on one side with the site of stimulation on the other side held constant near the middle of the array. Both of those curves showed more gradual increase in minimum ITD toward the cochlear apex than toward the base.

The advantages in noise reported by one of the subjects for a custom in-the-canal microphone system of his own design were confirmed and documented in free field speech reception studies.

III. Plans for the next quarter

Among the activities planned for the next quarter are:

- The beginning of studies with local bilaterally implanted subject ME-16.
- Continuing studies with local bilaterally implanted subject ME-12.
- The arrival of Dr. Xiaoan Sun, the Center's new electrical engineer.
- Presentation by Blake Wilson of a keynote lecture to the Seventh International Cochlear Implant Conference in Manchester, UK.
- Studies with a new bilaterally implanted subject, ME-17.
- Studies with percutaneous subject SR-9 to begin evaluations of a new type of processing strategy, including nonlinearities designed to mimic functions of the normal ear.
- Completion of arrangements with Duke University Medical Center and Cochlear Corporation for studies involving percutaneous access to experimental perimodiolar electrode arrays in four subjects.

IV. Acknowledgments

We thank volunteer research subjects NU-6 and ME-15 for their contributions to the work described in this report, and subject SR-3 for contributions this quarter to work to be described in a future report.

Appendix 1. Summary of reporting activity for this quarter

Reporting activity for this quarter, covering the period of April 1 through June 30, 2002, included:

An invited presentation by Dewey Lawson as part of the annual Prentice Bloedel Day (May 20) at the Virginia Merrill Bloedel Hearing Research Center of the University of Washington in Seattle.