Twelfth Quarterly Progress Report

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Speech Processors for Auditory Prostheses

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I. Introduction

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

Work and activities in this quarter included:

- Studies with subject ME10 during the three-week period beginning on July 16. This subject was referred to us by our colleagues in Vienna, Austria, and is a recipient of a COMBI 40 implant on one side and a COMBI 40+ implant on the contralateral side. The studies included measures of sensitivities to interaural timing and amplitude differences and evaluation of various processing strategies either to represent cues for sound localization or to exploit the availability of bilateral implants in other ways (see Quarterly Progress Report 4 for this project, for a detailed discussion of processing options for bilateral implants).

- A visit by Marcel Pok of the Vienna Cochlear Implant Team, in conjunction with the visit by subject ME10.

- Continued studies with local subject NU4, during the mornings of August 7-9. (NU4 is a recipient of Nucleus 22 devices on both sides; see QPR 4.) The studies with her included fitting of new ear-level processors and evaluation of various processing alternatives.

- Continued studies with Ineraid subject SR10, during the week beginning on August 13. The studies included (1) completion of prior studies to evaluate effects of changes in carrier rate and envelope cutoff frequency in CIS processors, using tests of consonant identification; (2) further tests, with TIMIT sentences, to evaluate effects of changes in the mapping functions used with CIS and other processors (see QPR 3 for initial results with two other subjects); (3) scaling of pulse rates, for unmodulated pulse trains presented in conjunction with conditioner pulses, for various levels (including zero) of the conditioners; (4) measures of intracochlear evoked potentials for single polarities of biphasic and monophasic-like pulses using a template subtraction procedure (the monophasic-like pulses were "split phase" pulses, with a 3 ms inter-phase gap and with equal charges for the two phases); and (5) measures of artifact (electric field) potentials at unstimulated electrodes for subthreshold pulses presented separately to each of the intracochlear electrodes.

- Continued studies with Ineraid subject SR9, during the week beginning on August 27. The studies included (1) completion of prior studies to evaluate effects of changes in carrier rate in CIS processors while holding the envelope cutoff frequency constant at 200 Hz, using a wide range of speech reception measures; (2) further tests, with CUNY sentences, to evaluate effects of changes in the mapping functions used with CIS and other processors; and (3) scaling of pulse rates, for unmodulated pulse trains presented in conjunction with conditioner pulses, for various levels of the conditioners.

- Continued studies with subject ME7 during the two-week period beginning on September 4. This subject was initially referred to us by our colleagues in Würzburg, Germany, and is a recipient of

COMBI 40+ implants on both sides. The studies with her included many of the measures listed above for subject ME10. (Initial studies with ME7 were for one week only, and thus included only a limited set of speech reception measures and no measures of sensitivities to the interaural difference cues.)

- Presentations of project results in several invited talks at the *2001 Conference on Implantable Auditory Prostheses*, held in Pacific Grove, CA, August 19-24

- Presentation of project results in (1) two other invited talks at the *Med-El US Investigators Meeting*, held in Quebec City, Canada, July 20-21, and (2) a contributed poster at the *2001 Conference on Implantable Auditory Prostheses*.

- Participation by Lianne Cartee in an "update" workshop sponsored by the Advanced Bionics Corporation, on a new interface system the company has developed for support of research studies with their CII implant device (August 23, during one of the open afternoons at the *2001 Conference on Implantable Auditory Prostheses*).

- Further development of tools for support of our studies, including (1) the Access database of speech processor designs and study results, initially described in QPR 10, and (2) monitor programs for implementing psychophysical test procedures for studies with recipients of bilateral CI24M implants.

- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.

- Continued preparation of manuscripts for publication, including invited contributions to the upcoming volume 4 of the *Annual Review of Biomedical Engineering* and to the upcoming book titled Auditory Prostheses, which will be a new addition in the ongoing series of books in the *Springer Handbook of Auditory Research*.

This quarterly report includes data from our most recent studies with bilaterally implanted subjects, including ME7, ME10, and NU4.

Results from other studies and activities conducted in this quarter will be presented in future reports.

II. Further studies regarding benefits of binaural cochlear implants

Previous reports on our studies of subjects with binaural cochlear implants have appeared in several Quarterly Progress Reports over the past five years (QPR 5 for previous contract N01-DC-5-2103, and QPRs 1, 4, and 9 for the current contract). In this report we shall

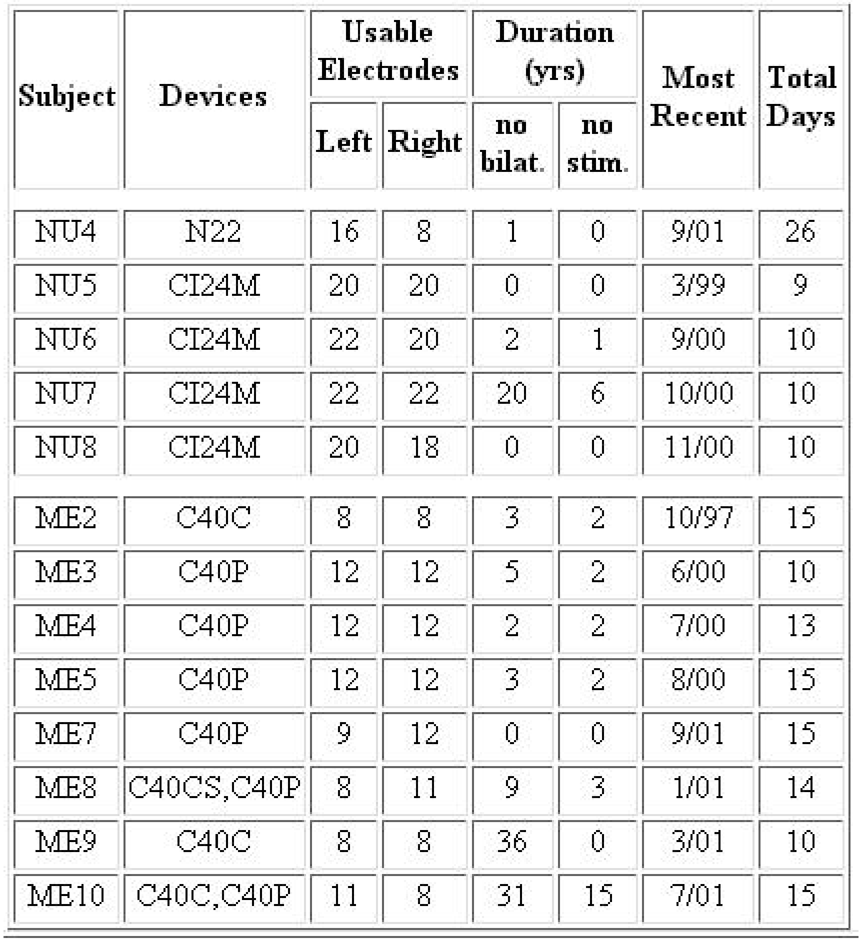
1. provide an updated profile of the 13 subjects studied thus far,
2. describe the preliminary studies that form the basis for our assignment of signals to electrodes -- both for psychophysical studies and processors,
3. summarize our interaural amplitude difference (IAD) and interaural time difference (ITD) studies and results to date, and
4. discuss our current experimental methods and findings for binaural stereophonic reception of speech in the presence of noise from various directions.

1. Binaural cochlear implant subjects studied thus far

Of the 13 cochlear implant patients who have participated in our studies to date, 5 were implanted with Nucleus 22 or 24 devices manufactured by Cochlear in Australia, and 8 with Combi 40 or Combi 40+ devices manufactured by Med-El in Austria. The codes by which these subjects are identified in our reports indicate the respective implant manufacturer through NU and ME prefixes.

Device, history, and participation data are summarized for all 13 subjects in Table 1.

Table 1. Research subjects with bilateral cochlear implants.



Subject	Devices	Usable Electrodes		Duration (yrs)		Most Recent	Total Days
		Left	Right	no bilat.	no stim.		
NU4	N22	16	8	1	0	9/01	26
NU5	CI24M	20	20	0	0	3/99	9
NU6	CI24M	22	20	2	1	9/00	10
NU7	CI24M	22	22	20	6	10/00	10
NU8	CI24M	20	18	0	0	11/00	10
ME2	C40C	8	8	3	2	10/97	15
ME3	C40P	12	12	5	2	6/00	10
ME4	C40P	12	12	2	2	7/00	13
ME5	C40P	12	12	3	2	8/00	15
ME7	C40P	9	12	0	0	9/01	15
ME8	C40CS,C40P	8	11	9	3	1/01	14
ME9	C40C	8	8	36	0	3/01	10
ME10	C40C,C40P	11	8	31	15	7/01	15

As shown in Table 1, most of the subjects have identical devices bilaterally [column 2], and most have full insertions of electrode arrays on both sides [columns 3 and 4]. Their periods of experience without binaural stimulation range up to 36 years [from profound loss in the first ear until activation of the implant on the second side, column 5]. The periods they have experienced without any significant auditory stimulation range up to 15 years [from profound loss in the second ear until activation of the first implant, column 6]. Each subject was last seen by us since late 1997 [column 7] and has been studied in our laboratory for at least two weeks [column 8].

The range of etiologies for these subjects is displayed in Table 2. It includes three cases of Ménière's disease, several skull fractures, and several other diagnoses of varying certainty.

Table 2. Available information for each subject regarding etiology of deafness.

Subject	Etiology of deafness
NU4	Listeria rhomboencephalitis
NU5	acute noise exposure, further loss during subsequent pregnancy
NU6	onset coincident with poliomyel(oencephal)itis, familial history of deafness
NU7	Ménière's disease
NU8	Ménière's disease
ME2	gradual progressive
ME3	sudden loss of unknown cause
ME4	bilateral basal skull fractures
ME5	otosclerosis
ME7	bilateral temporal bone fractures
ME8	Ménière's disease
ME9	onset coincident with measels, otitis media; familial history of deafness
ME10	temporal bone fracture; contralateral loss of unknown cause

No results for subjects ME9 and ME10 have been included in any of our previous reports.

2. Preliminary studies to support assignment of signals to electrodes

After initial determination of threshold and most comfortable stimulation amplitudes for selected pulse rates and durations on each usable electrode -- including careful loudness balancing at MCL against a single reference stimulus -- we conduct a systematic study of pitch ranking among ipsilateral and contralateral pairs. The results for all 13 subjects are summarized in Figure 1, with left electrodes on the left side and right electrodes on the right in each case. Differences in vertical position for a given subject denote differences in pitch. Higher pitches are toward the top; the numbers are those appropriate to each manufacturer's electrode labeling convention.

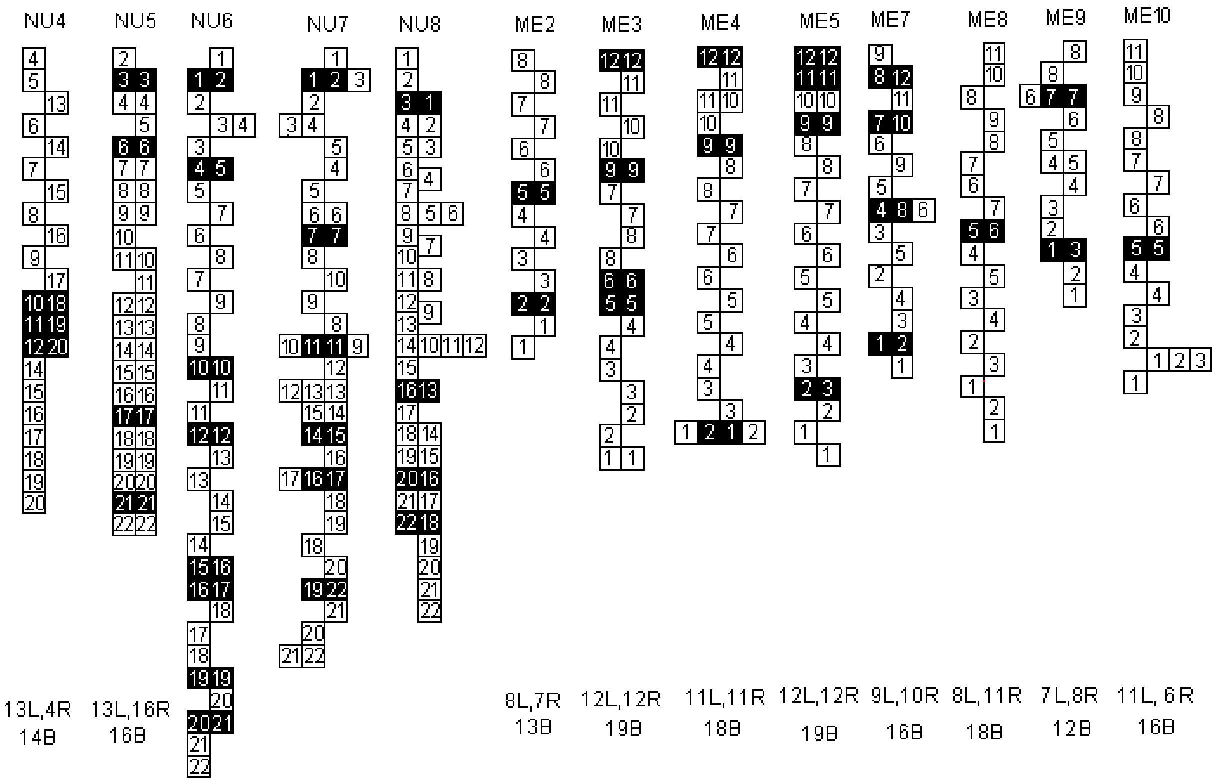


Figure 1. Pitch ranking among electrodes for each subject.

Each indicated difference is significant for the Med-El subjects, but that is not always true for the more closely spaced adjacent electrodes in the Nucleus subjects. Differences in vertical position ***between*** subjects are meaningless, of course. In most cases, maximum numbers of pitch distinct electrodes were determined for each side alone and for both sides combined. Those numbers are indicated below the corresponding columns.

Bilateral pairs of electrodes that cannot be discriminated on the basis of pitch are valuable for interaural studies. Such pairs are highlighted in Figure 1. Our current practice is to examine further all contralateral pitch-matched pairs identified in the initial pitch ranking studies. The pitch indiscriminability of each such pair is evaluated statistically using an adaptive procedure illustrated in Figure 2.

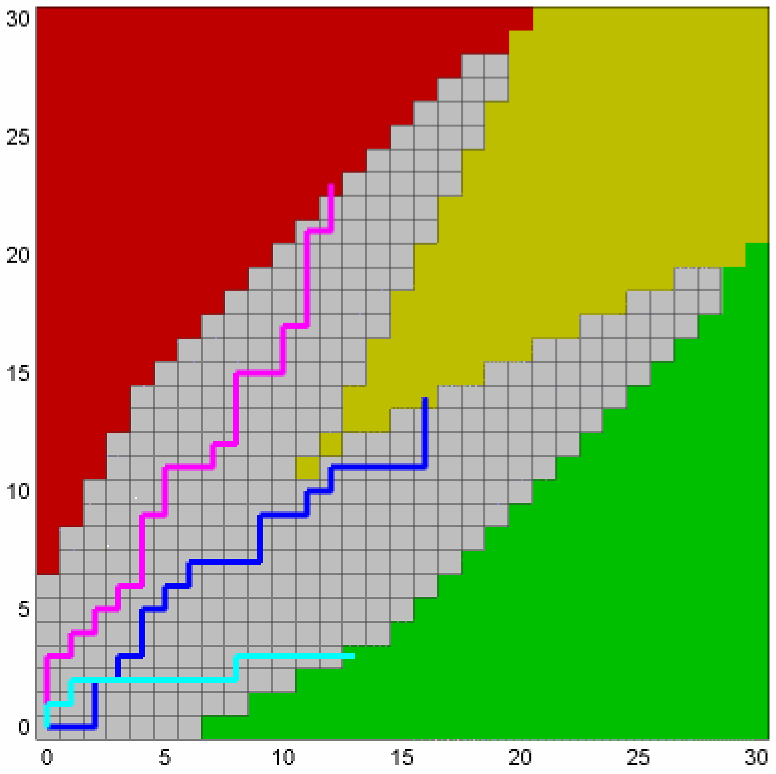


Figure 2. Examination of candidate electrode pairs for pitch matching.

The two electrodes are stimulated successively in random order, the subject is asked whether the first or second was higher in pitch, and this continues until a statistically significant finding is achieved as to discriminability. The course of three such determinations is shown graphically in Figure 2, each represented by a trajectory beginning at the lower left corner of the grid. At each point on such a trajectory the horizontal position indicates how many times the right electrode stimulus had been judged higher, and the vertical position the corresponding number of left higher judgments. A determination occurs when a trajectory reaches one of the large regions at the other three corners. Reaching the region at the upper right (shown as yellow in the HTML version of this report) signifies indiscriminability. [See, for instance, I. D. J. Bross, Biometrics **8**, 188-205 (1952).]

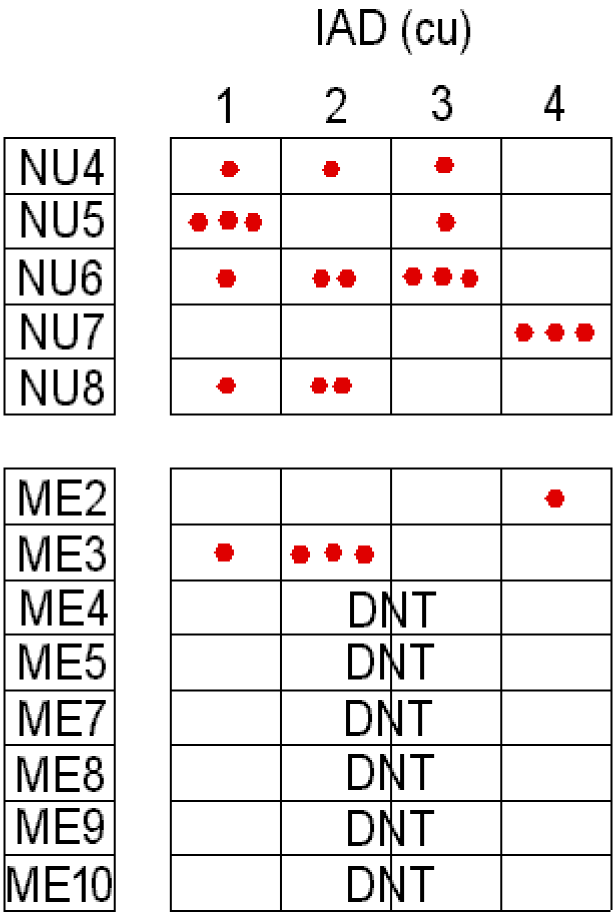
3. Interaural difference studies

One use of such matched pairs is interaural amplitude difference (IAD) studies. Simultaneous 300 ms pulse bursts are delivered to both electrodes, one ear stimulated at MCL and the other at a reduced amplitude. In a two alternative forced choice test, the subject is asked whether the sound came more from the left or more from the right. A response indicating the side that received the unreduced MCL stimulation is scored as a correct lateralization. Such scores are plotted as a function of amplitude reduction, measured in units of the smallest amplitude steps available from the implanted devices --

"clinical units" in the case of NU devices and "current units" in the case of ME devices.

Figure 3 summarizes such data for seven of our subjects. Each dot (red in the HTML version) indicates a study involving a pitch-matched pair of electrodes that demonstrated the subject's ability to lateralize reliably on the basis of the IAD shown at the top of the corresponding column.

Table 3. Lateralization on the basis of Interaural Amplitude Difference.



	IAD (cu)			
	1	2	3	4
NU4	●	●	●	
NU5	●●●		●	
NU6	●	●●	●●●	
NU7				●●●
NU8	●	●●		
ME2				●
ME3	●	●●●		
ME4		DNT		
ME5		DNT		
ME7		DNT		
ME8		DNT		
ME9		DNT		
ME10		DNT		

Five of the seven subjects tested could lateralize on the basis of the smallest amplitude differences allowed by the implanted device, at least on some pitch matched pairs.

We have lowered the priority of this formal study in more recent visits, but our strong impression -- based on the loudness balancing procedures that precede our pitch ranking studies -- is that lateralization on the basis of the smallest available amplitude differences is not at all unusual. Thus sensitive IAD cues are available to bilateral CI users -- in independent as well as coordinated processors -- and there is reason to think that such users might benefit from the availability of even smaller amplitude differences.

Another use of carefully matched bilateral pairs of electrodes is in interaural time difference (ITD) studies. In this case the pairs are both pitch-matched and loudness-balanced. 300 ms pulse trains with identical pulse rates and durations are presented to the two electrodes, one delayed with respect to the other. We record percent lateralization to the side receiving the earlier stimulus as a function of interaural delay. Our current practice is to fit a weighted logistic function to the percent lateralization scores and record the 75% point of that function as the minimal ITD supporting reliable lateralization for the selected electrode pair and stimulus. Figure 3 is an example of such a fit for a particular combination of electrode pair and stimulus.

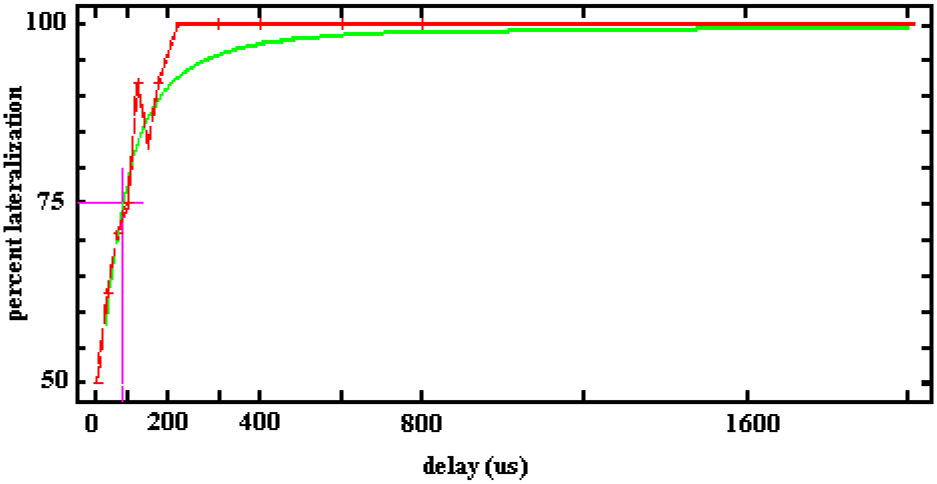


Figure 3. Example of determination of minimum interaural time difference for lateralization, using a logistic fit.

The data points are connected by straight lines (red in the HTML version) and the weighted logistic fit is shown as a (green) curve. The delay corresponding to the 75% point on that curve -- in this case 62 us -- is the ITD value determined by the procedure.

In Table 4 is a summary of ITD data for all 13 subjects. Dots (red in the HTML version) indicate the range of delays into which each ITD determination fell.

Table 4. Lateralization on the basis of Interaural Time Difference

ITD (µs)

	50	150	300	500	1k	2k
NU4		●●	●			
NU5	●	●●	●			
NU6	●	●●●	●●	●		
NU7			●●	●●●●		
NU8	●●●●	●●				
ME2			●	●		●●●●
ME3		●●		●●		
ME4	●	●●●	●	●	●●	
ME5	●	●●	●	●●	●●	●●●●
ME7	●	●●●	●●	●	●●●	
ME8	●●●●●	●●●●●●●●●●●●●●●●				●
ME9						
ME10	●	●●			●	

Eight of the 13 subjects can lateralize on the basis of 50 µs or less ITD for some condition(s). This corresponds to a five-degree or less difference in direction of sound incidence. Ten of the 13 can lateralize on the basis of delays of 150 µs or less, and 12 of the 13 on the basis of ITDs less than 300 µs. One of the 13 subjects (ME9) could not lateralize reliably for any ITD with any stimulus we devised.

The data summarized in Table 4 include examples of all three different types of stimuli used thus far in our ITD studies. With unmodulated pulse trains, as portrayed in Figure 4, we have observed lateralization for ITDs as brief as 50 µs.

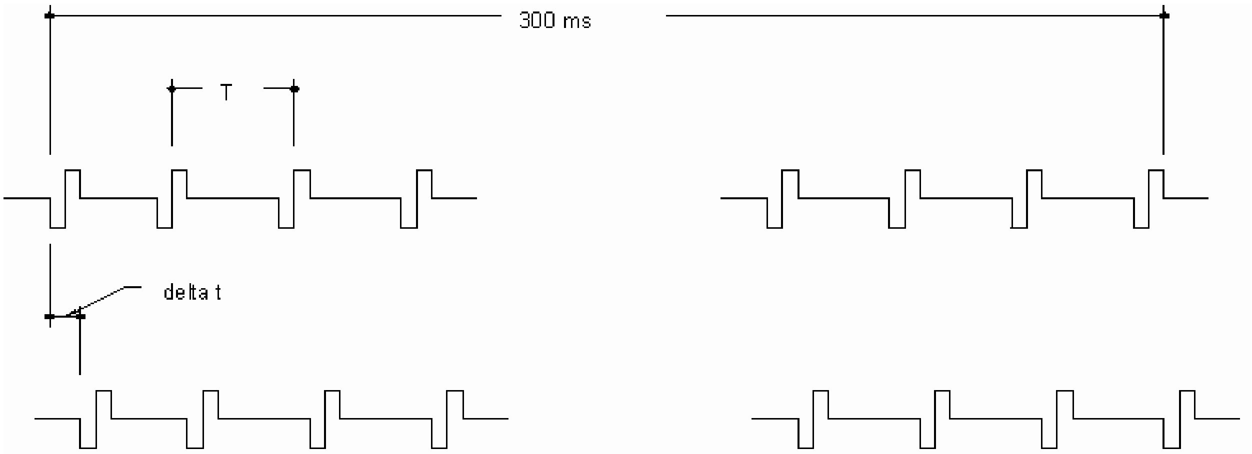


Figure 4. Interaural time difference stimuli: unmodulated pulse trains

With this type of stimulus, the pulse bursts presented to the two sides are identical in terms of timing, with the second begun asynchronously after the prescribed delay.

We have begun some studies in which continuous pulse trains are modulated by envelopes that are offset in time. The continuous pulse trains may have identical rates and durations with pulses that are synchronized or not between sides, or the pulses can have different rates and durations. Thus far, the smallest ITDs that have supported lateralization for this type of stimuli have been a couple hundred µs.

We have studied both these stimulus types for selected pairs of electrodes -- pitch matched or, occasionally, intentionally offset from pitch matched locations. But our shortest observed ITD lateralizations to date have been for a third type of stimulus -- brief envelopes repeated at a rate of 50/s, produced by inputting pulses to CIS processors at that rate.

Figure 5 displays oscilloscope traces of actual outputs from a single left-ear Combi 40 implant, controlled by a clinical CIS processor.

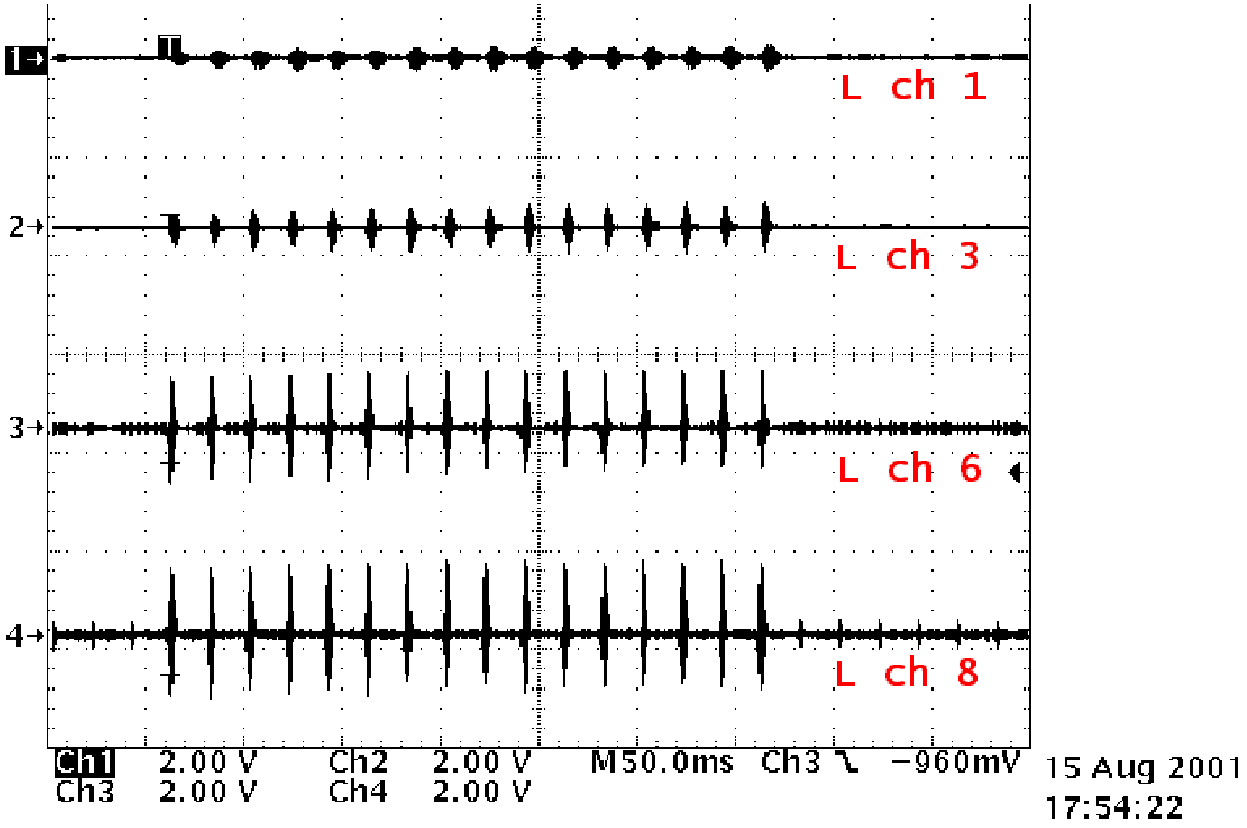


Figure 5. Unilateral CIS outputs for 50 p/s input train

The input signal to the processor was a 300 ms burst of brief pulses at a rate of 50/s, so on this 50 ms/division display, we see a 20 ms interval between successive envelopes in the output signals. The display includes outputs to the electrodes assigned to channels 1 (at the apical, low-frequency end), 3, 6, and 8. For clarity in this and subsequent illustrations, we have set threshold stimulation levels to zero. In Figure 6 we show the same signals at a higher resolution time scale.

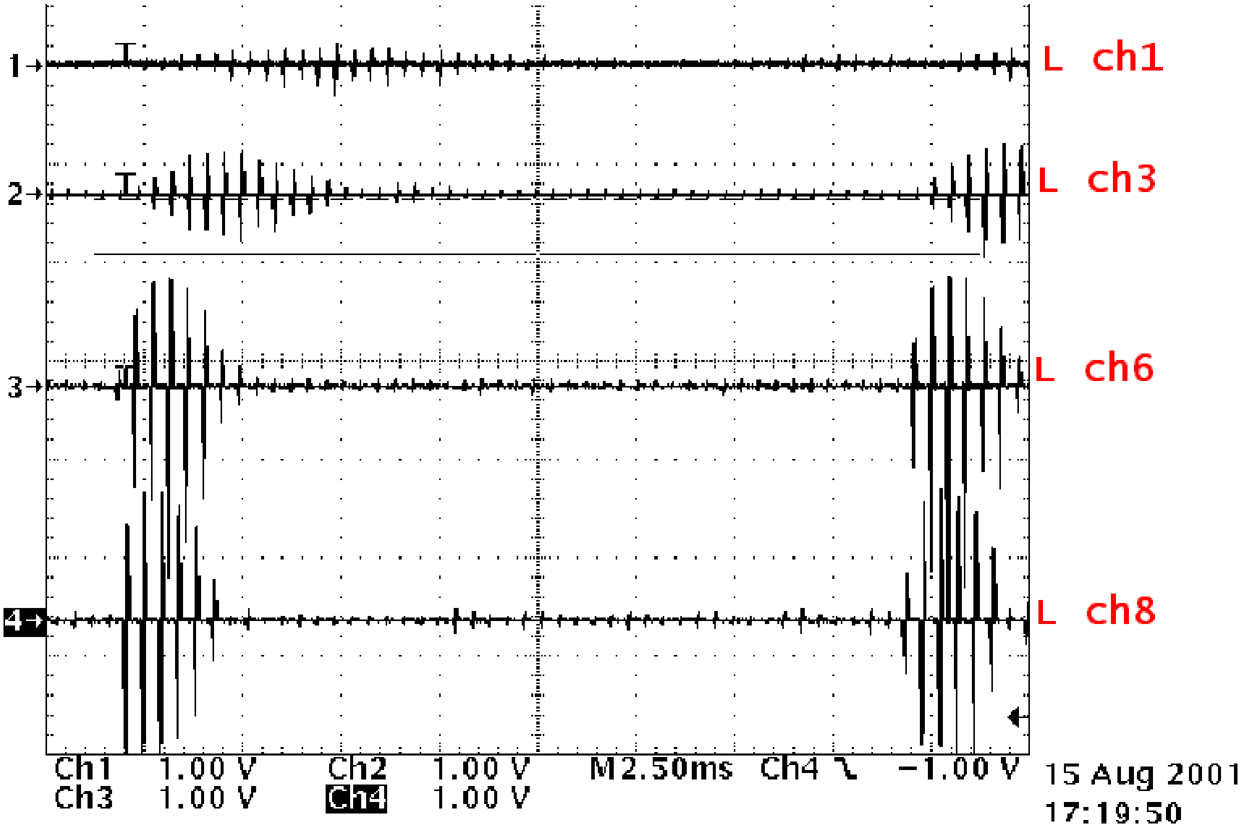


Figure 6. Unilateral CIS outputs for 50 p/s input, detail.

Now the display scale is 2.5 ms/division, and we can see the individual 40 µs/phase biphasic pulses at about 2000 p/s. One complete set of envelopes can be seen, and part of another, produced by the processor in response to successive input pulses at 50/s.

Notice the different envelope delays for different channels on this one side, due to the different bandpass filters.

In Figure 7 we compare channel 6 and 8 outputs for both sides of a bilateral processor system.

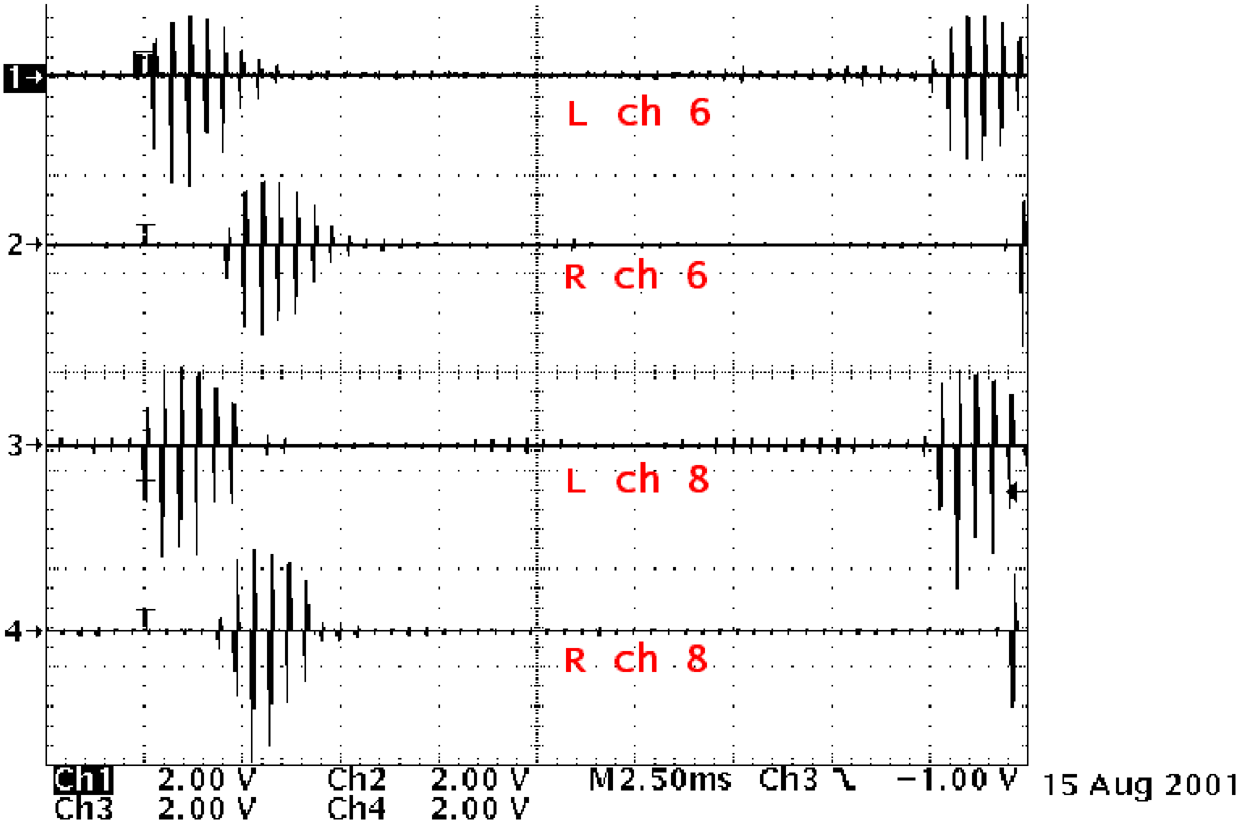


Figure 7. Bilateral CIS outputs, 50 p/s, ITD = 2 ms.

The time scale is the same as in Figure 6. We now display the left and right channel 6 outputs and the left and right channel 8 outputs. The left and right processors have approximately the same rate, but are not synchronized, so the relative phase between pulses on the two sides varies in time. The ITD is 2 ms in this example, allowing us to see a clear difference in envelope timing between the two sides for each of the two channels shown.

In Figure 8 we reduce the ITD to 100 μs.

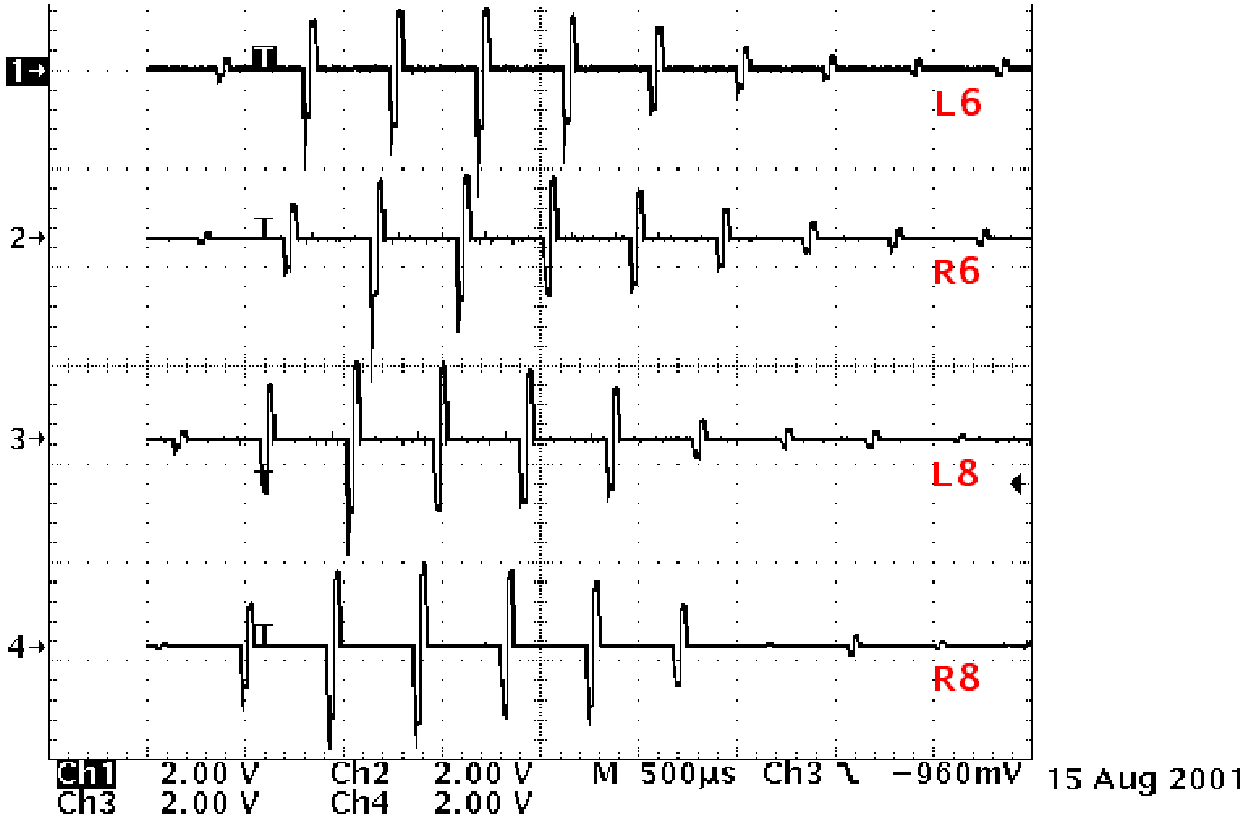


Figure 8. Bilateral CIS outputs. 50 p/s, ITD = 100µs

The time scale is now 500 µs/division, so the 100 µs ITD is only 1/5 division on this display. As in the previous case, pulses are not synchronized between the two sides. The ITD is much less than the interpulse interval. It is less than the interchannel timing differences among the bandpass filters. And of course the ITD is much less than the envelope duration. It would be a challenge to measure the ITD from this display.

Figure 9 is a schematic diagram of the situation, depicting the envelopes as well as the resulting pulse amplitudes.

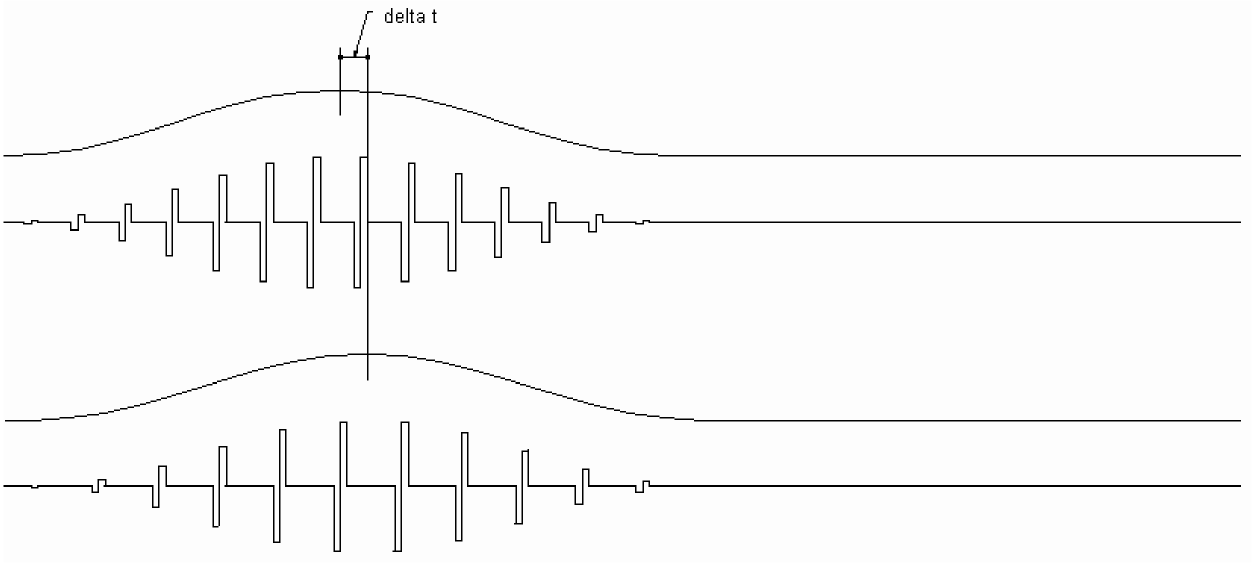


Figure 9. Interaural time difference stimuli: modulated independent (non-synchronized) pulse trains

Two of our subjects lateralized on the basis of ITDs of only 25 µs with such signals.

While we do not understand how such a result is being achieved by those subjects, we have a long list of follow-up studies designed to narrow the range of possibilities. It may be, for instance, that the CNS is exploiting one or more of the uncontrolled variations across successive samples to improve ITD resolution. Any asynchrony between the sides, for instance, insures that slightly different points on the envelope will be represented by modulations in response to successive input pulses. Another possibility is that the CNS is integrating and utilizing information from multiple matched sites across the two sides.

4. Speech reception in noise using binaural implants

Figure 10 is an example of the standard set of speech reception data we now use to assess processor performance in noise.

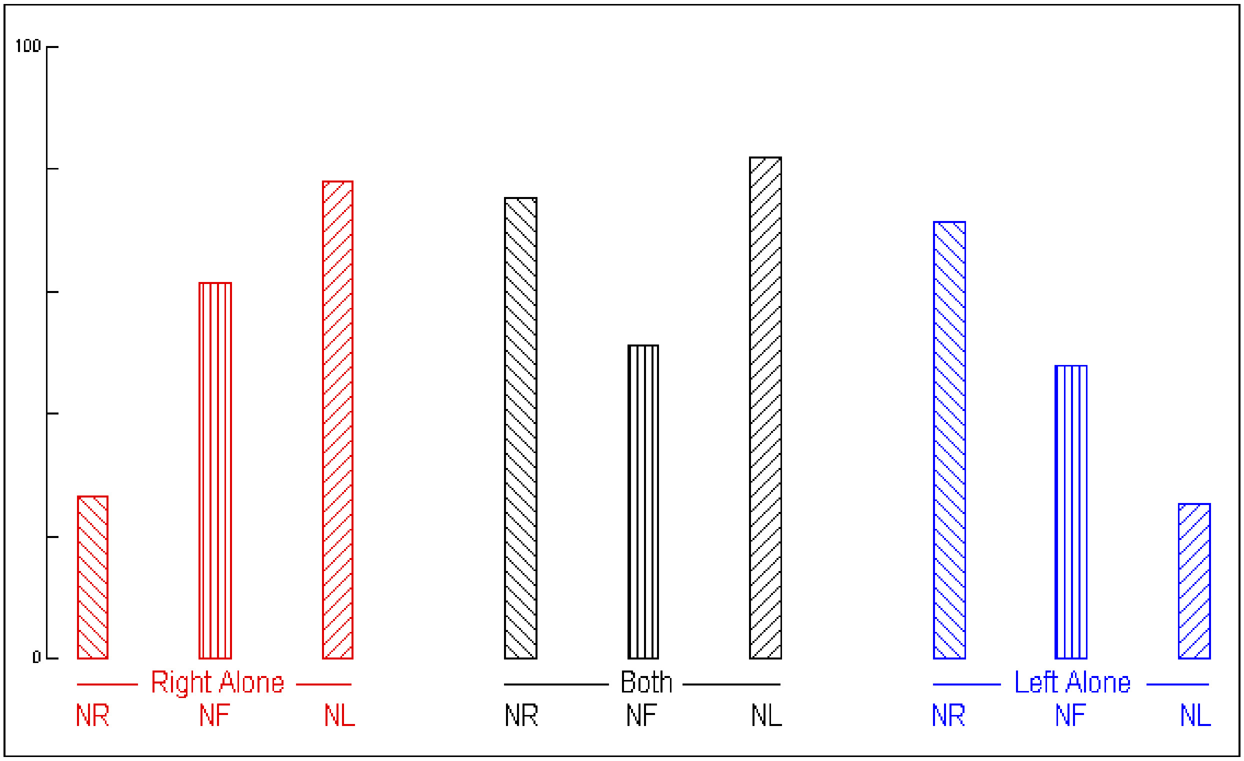


Figure 10. ME10 Sentence Data: 3 processor conditions x 3 noise conditions

The bars represent percent correct scores on a speech identification test. If the arrangement of the bars seems strange to you, try thinking of the subject as facing you, with his/her right ear to your left.

The three groups of bars are for tests administered with the right ear processor alone, with both processors, and with the left ear processor alone.

Signals are directly injected in the left ear and right ear processor inputs, after head-related transfer function (HRTF) processing of the speech signal (always from the front) and CCITT speech spectrum noise (from 90 degrees to the right [NR], from the front [NF], and from 90 degrees to the left [NL]). [The hatching on the bars is intended to suggest noise direction.]

We use a variety of speech materials in English and German. In this example, the display is of word correct scores for German sentences, on a scale of zero to 100%, for subject ME10.

In several figures to follow we shall reproduce this same set of data, but highlight different insights one can gain from various comparisons among the bars. We begin, in Figure 11, by considering each ear alone and comparing ipsilateral and contralateral noise conditions.

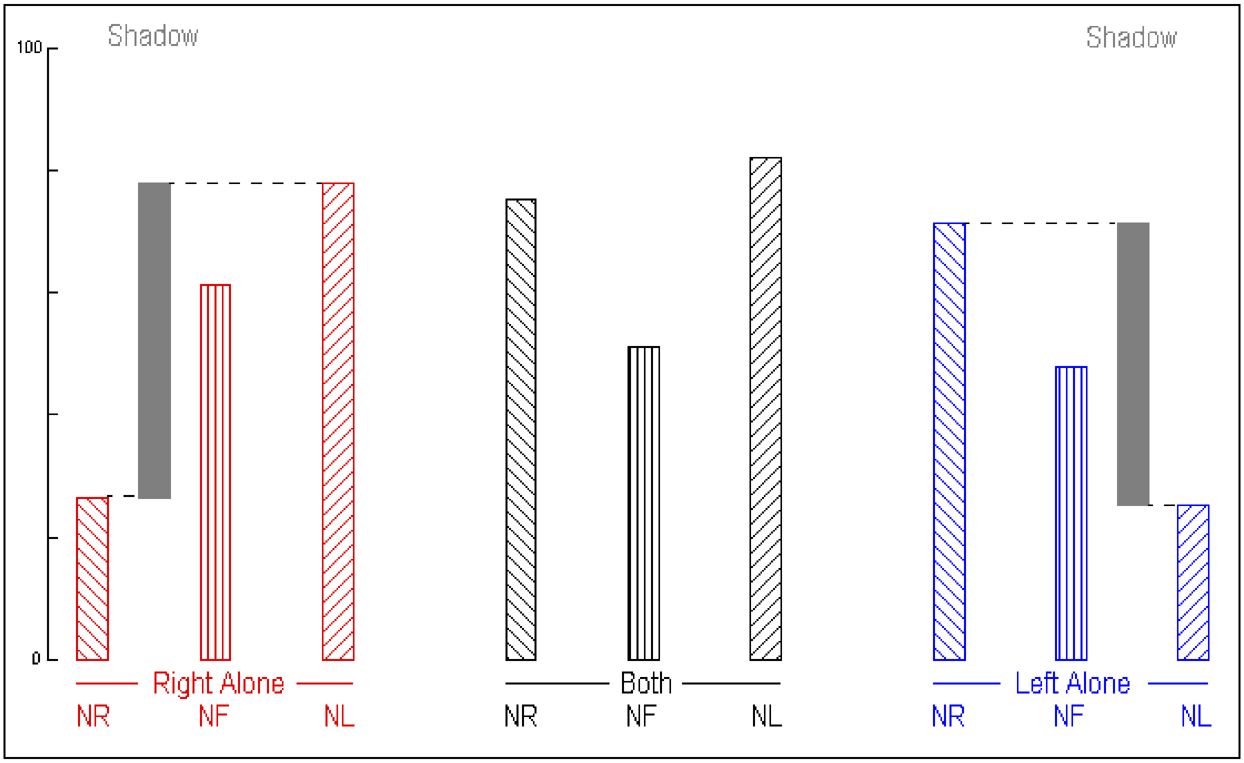


Figure 11. Same sentence data: head shadow effects

The contralateral noise condition often supports better performance because of the acoustic shadow cast by the listener's head. Performance with the right ear alone, for instance, is better when noise is from the left side, and *vice versa*. This **Head Shadow** effect -- shown in Figure 11 as solid bars (dark grey in the HTML version) -- is strongest for frequencies high enough that the corresponding wavelengths in air are small compared to the head's cross section.

Next, in Figure 12, we compare the three conditions for which noise comes from the listener's front.

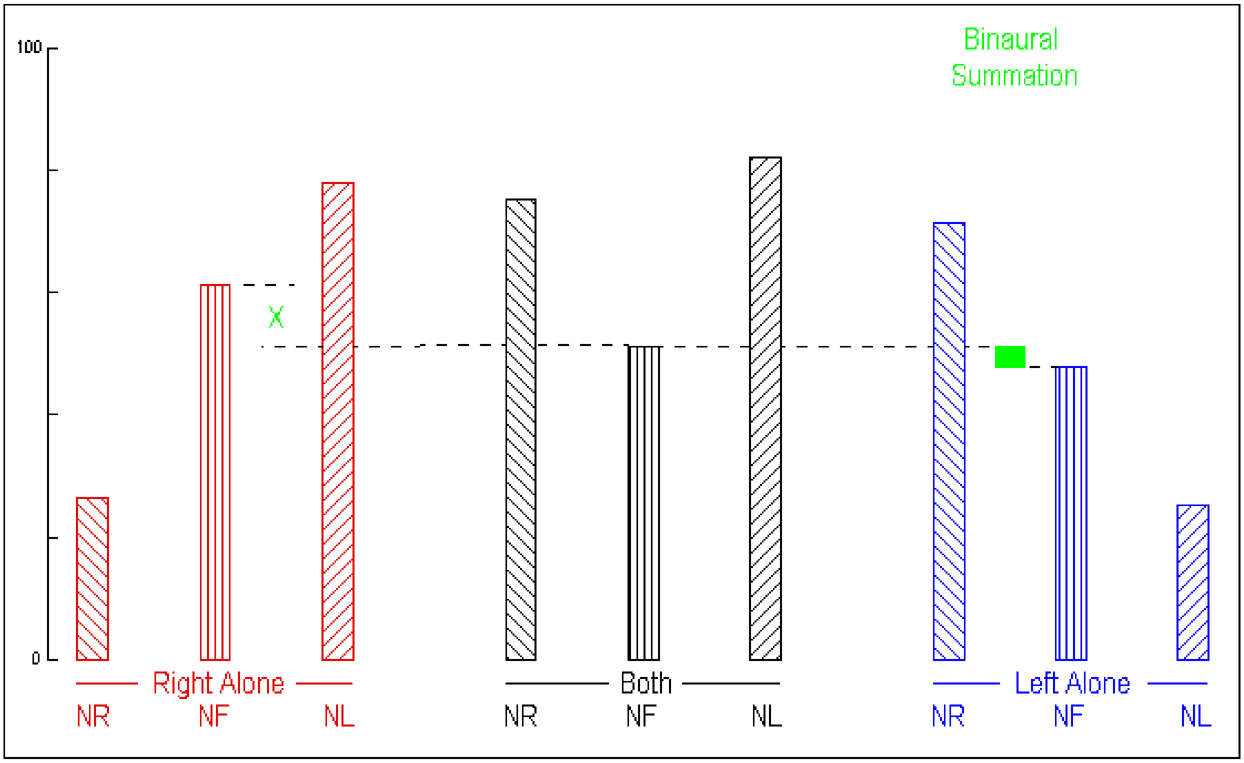


Figure 12. Same sentence data: binaural summation effects

If performance is improved by adding the second processor, that is attributed to **Binaural Summation** effects. Here this is true on one side but not the other. While adding the right processor improves performance over that obtained with the left alone, performance with the right processor alone is substantially better still. Thus the solid (green) bar in Figure 12 marks a small binaural summation effect on the left side but the corresponding difference is negative on the right side and there is no such effect.

For noise from the left and noise from the right, let us now compare performance with the sheltered opposite ear alone to that obtained with both ears. This is shown in Figure 13.

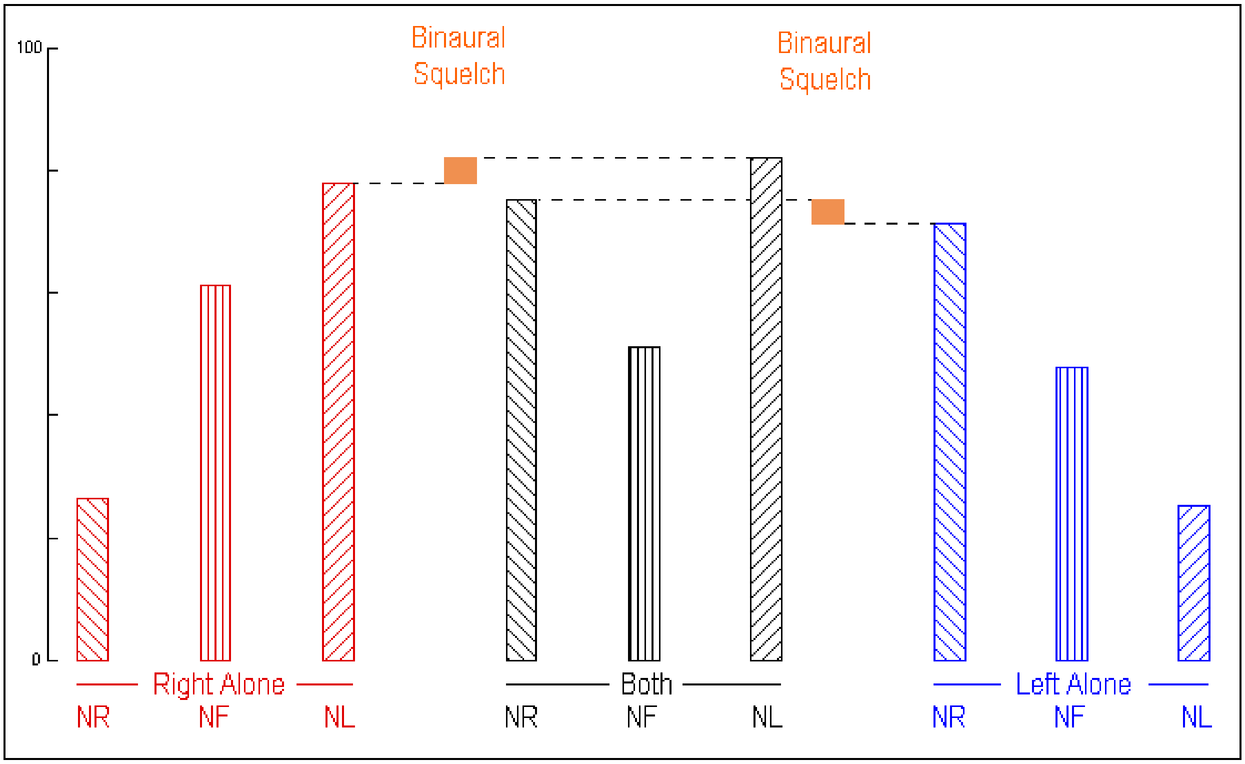


Figure 13. Same sentence data: binaural squelch effects

If performance is improved by adding a signal from the side nearer the noise source, the effect is referred to as **Binaural Squelch**, as marked by the solid (orange) bars in Figure 13.

Finally, Figure 14 demonstrates **Binaural Benefit** -- any improvement, using both processors, when the noise is from a different direction than the speech.

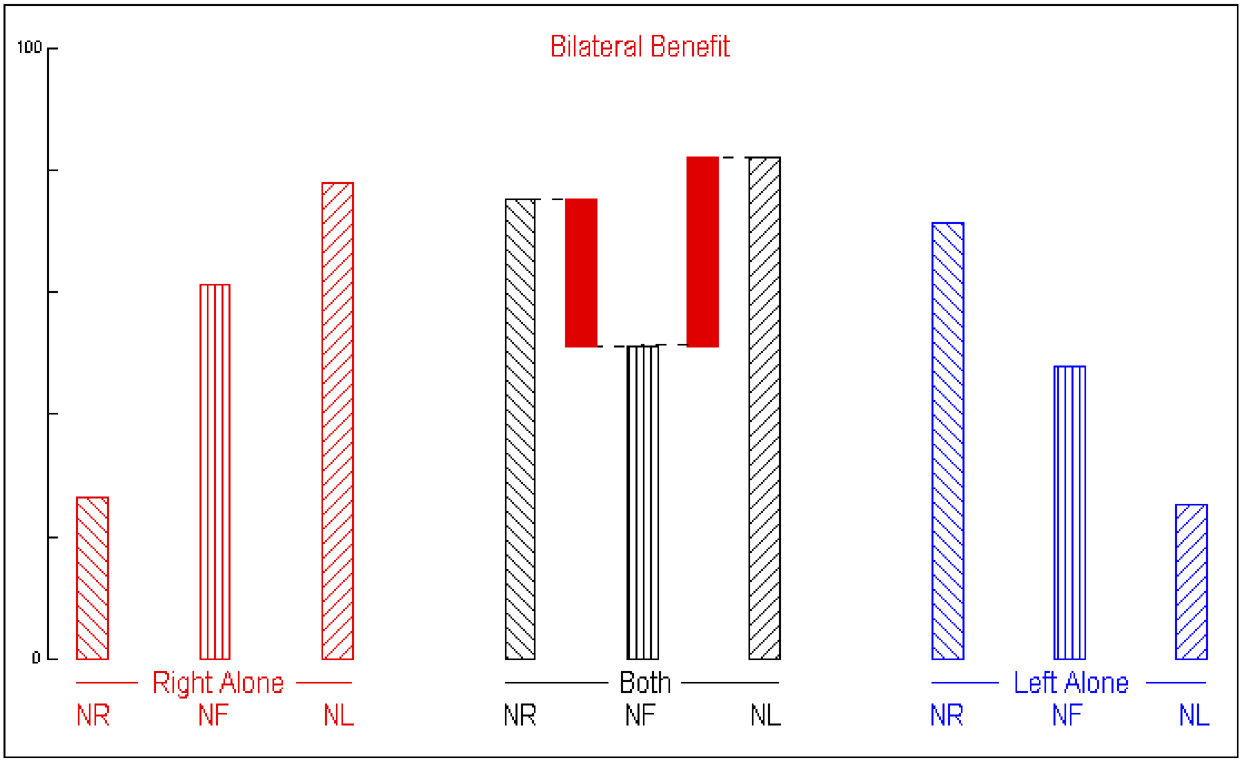


Figure 14. Same sentence data: bilateral benefit

The solid (red) bars measure the binaural benefit.

While it may be tempting to document only the three conditions using both processors and base assessments of processing strategies solely on bilateral benefit, we shall see that information from the unilateral processor conditions as well can be crucial to a meaningful assessment.

An alternative approach to the analysis of these nine-measurement representations of binaural performance is one suggested to us by a consultant to our contract, Sig Soli of the House Ear Institute. That approach looks separately at **Binaural Advantage** with and without Spatial Separation, and at **Spatial Separation Advantage** for each ear separately and for both ears together.

As shown in Figure 15, Spatial Separation Advantage is easily read from the data display, since it involves only adjacent bars. The solid bars (green in the HTML version) indicate the magnitude of the advantage.

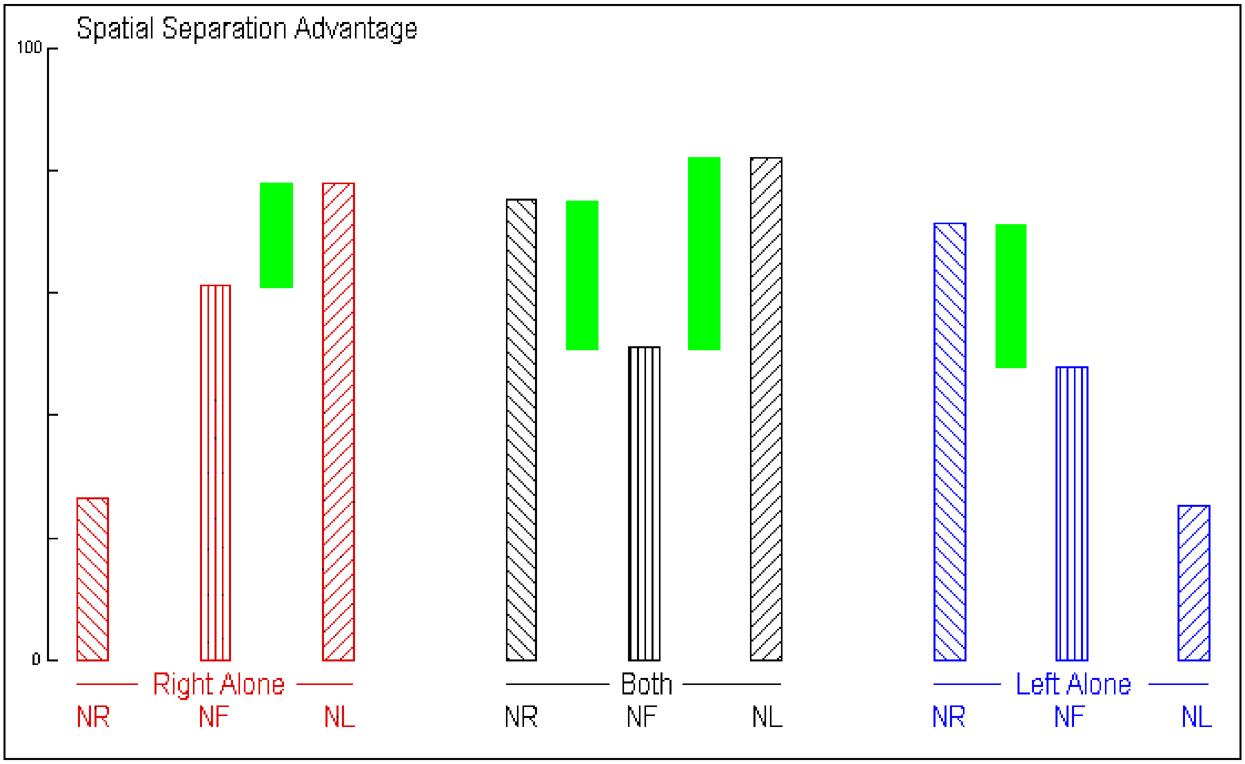


Figure 15. Same sentence data: spatial separation advantage

For the right and left single ear alone cases, the Spatial Separation Advantage is simply the improvement realized by arranging for the noise come from the side opposite the listening ear rather than along with the speech signal from the front. In some cases, a person with a right ear cochlear implant, for instance, may be able conveniently to position him/herself so that a competing conversation is to the left. In other circumstances that may be impossible without moving to the far side of the source of the signal or of the source of the noise

In the binaural case, extending our example, the user can obtain at least the lesser of the two Spatial Separation Advantage values shown without the need for a major relocation within a room.

In the absence of spatial separation -- when the source of the competing noise is truly and irrevocably coincident with the source of the speech signal -- there may yet be a Binaural Advantage. The relevant comparison in that case is between each ear alone and both ears together, all for noise from the front, and the Binaural Advantage is identical to what we called Binaural Summation in the context of our initial analysis scheme (see Figure 12 above).

When Spatial Separation is available, however, Binaural Advantage offers a very useful additional perspective on speech reception performance. In that case, the performance comparison is between each single ear and both ears, for noise from the right and from the left. A display from that perspective is shown in Figure 16: the solid bars (green in the HTML version) indicating the magnitude of the advantages.

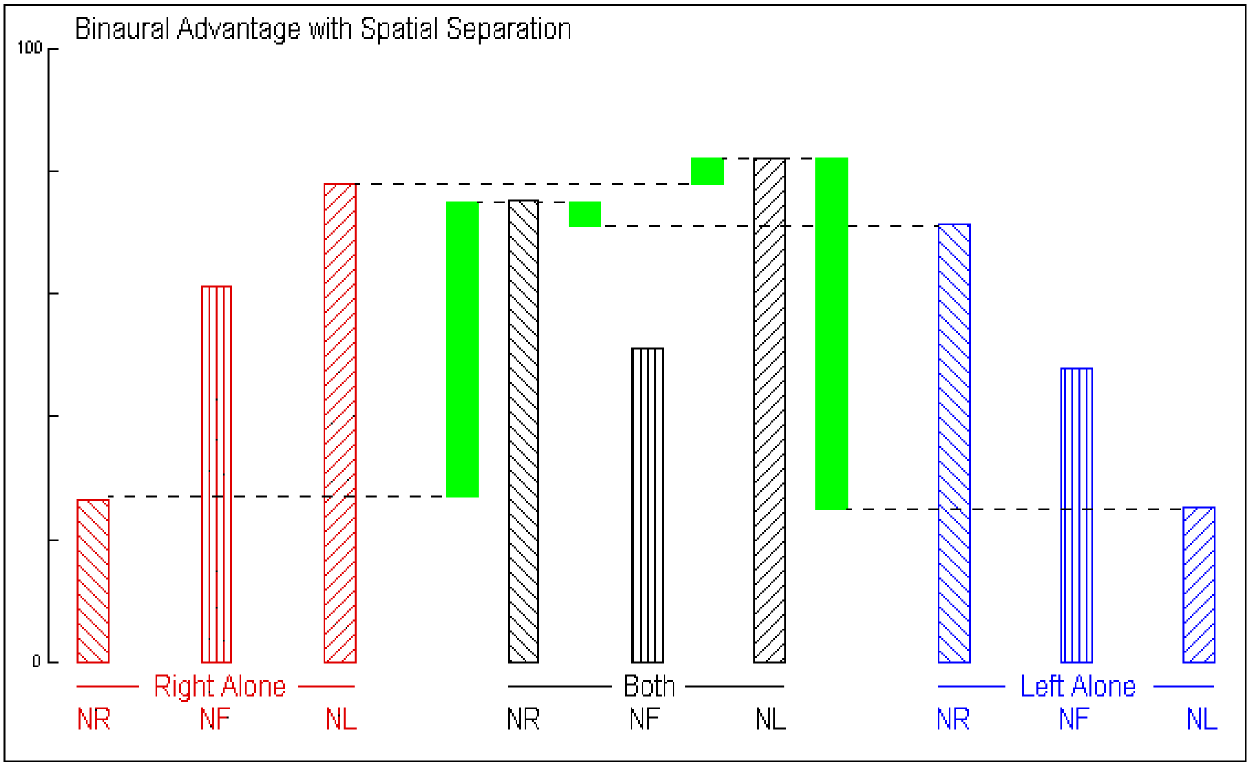


Figure 16. Same sentence data: binaural advantage in the presence of spatial separation

This type of display provides perhaps the most direct answer to the fundamental questions "*What difference does binaural processing make for this patient when directionally distinct noise is present?*" and "*How does this patient's performance in noise vary depending on which side the noise comes from?*" The larger advantages -- indicating the improvement of binaural hearing over hearing with the more noise-exposed ear alone -- are, typically, largely due to the head shadow effect. The smaller advantages of binaural hearing over an optimally oriented single ear represent the effect referred to earlier as Binaural Squelch.

Another advantage of this type of display -- involving six of the total nine measurements we use to characterize binaural hearing -- is that it is sensitive to the enormous practical consequences of a dominant ear, which as we shall see can be missed if only the Binaural Benefit of Figure 14 is considered.

In Figure 17 we show the same set of data one more time, with all the effects described in our initial analysis displayed simultaneously.

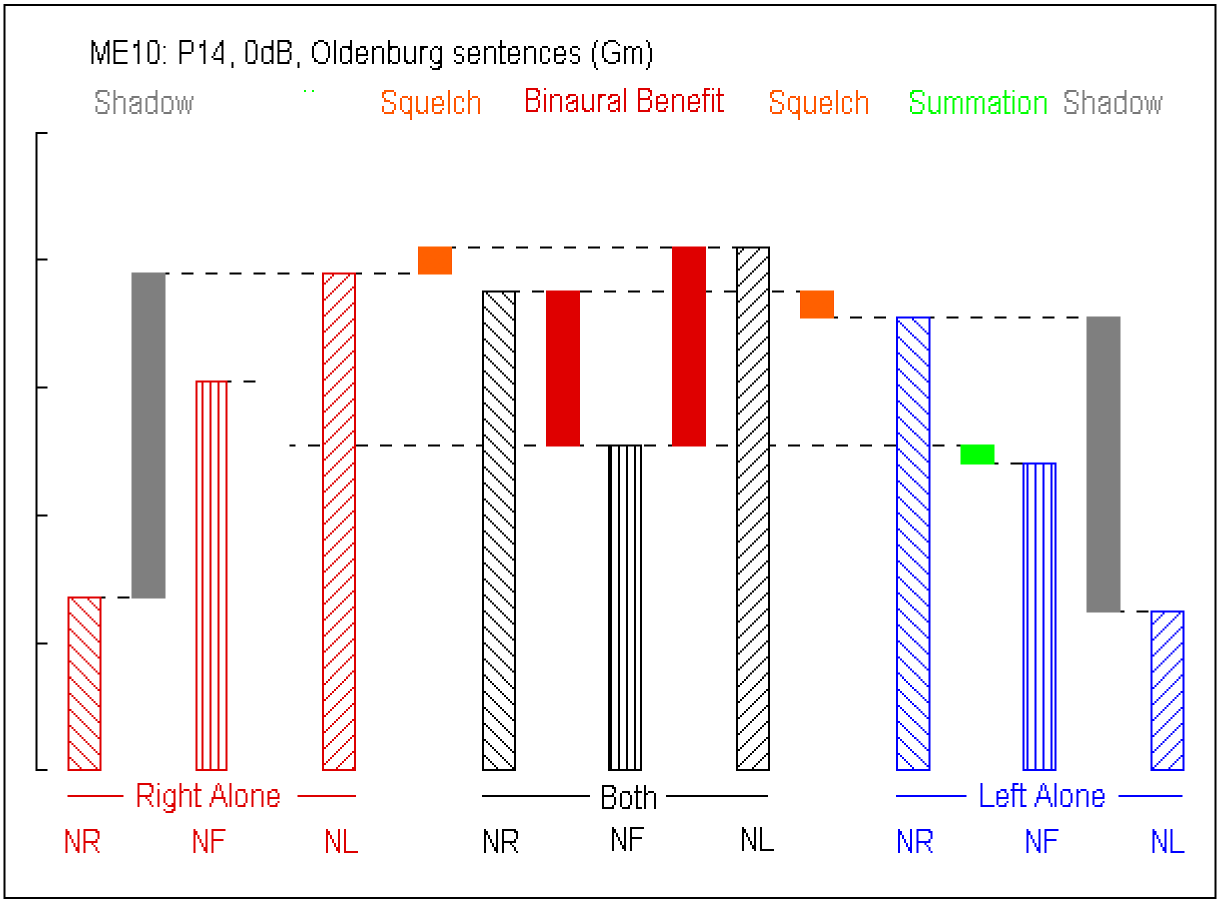


Figure 17. Same sentence data (subject ME10 and CIS processor: 6 channels Left, 6 channels Right; pulses synchronized between the two sides). Summary of contributions to binaural effects.

We shall use displays like those of Figures 17 and 16 to illustrate differences among various bilateral processors in several of our subjects. Also of interest will be the relative utility of (1) an indication of Binaural Benefit alone (as in Figure 14, also included in the center of Figure 17; involving only three measurements), (2) a display of Binaural Advantage in the presence of Spatial Separation (as in Figure 16; involving six measurements), and (3) exhibition of the full range of possible contributing mechanisms (as in Figure 17; requiring all nine measurements).

The data used for our introduction to these forms of display have been for 6 channel CIS processors on both sides, with identical pulse rates and durations, and with pulses synchronized between the sides (*i.e.*, under the control of a single research processor). As shown in Figure 17, the labeling at the top of each display will include a code identifying the subject (here ME10), a number identifying the design of the speech processor(s) involved (here a research processor P14 was used), the signal to noise ratio in decibels (here 0 dB), and a description of the test materials (in this case, percent correct word identification using the German language Oldenburg sentences).

The same processors' performance at a medial consonant identification task displayed in the same ways in Figure 18.

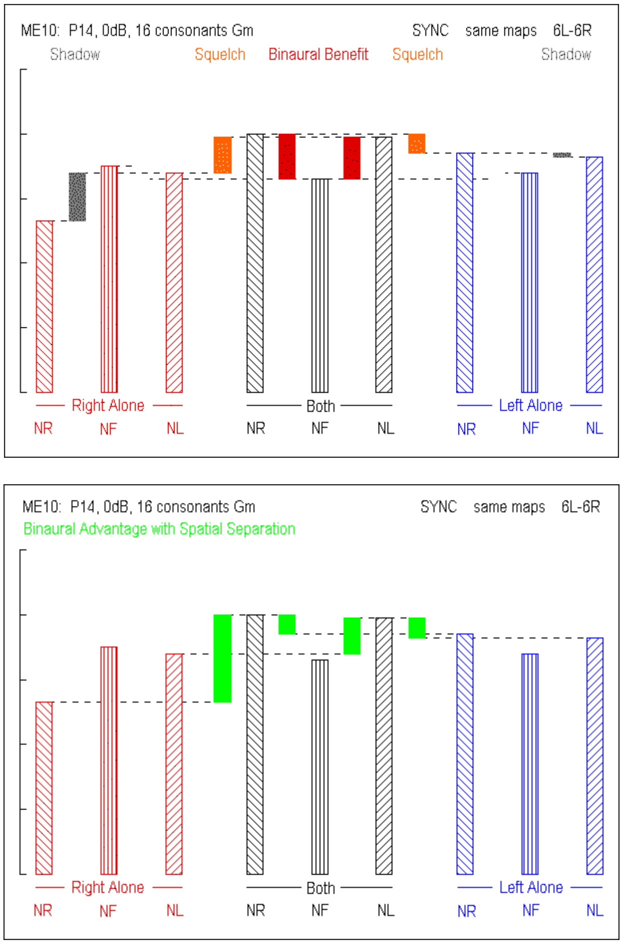


Figure 18. Consonant recognition data for same subject (ME10) and same CIS processor: 6 channels Left, 6 channels Right; pulses synchronized between the two sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below).

Here, too, we have a clear picture of better performance for this subject with bilateral stimulation using this processor design. The standard deviations of the mean for all such data that we shall show in this report are two to three percent typically, four percent at the most. The display scale will be zero to 100% correct in each case.

In considering the comparisons of speech reception in noise that comprise the remainder of this report, it will be helpful to keep two important points in mind:

1. It is crucial to assess each patient individually. Averaging performance data across patients can be extremely misleading.
2. Noise levels for assessment must be carefully chosen both to (a) allow sensitive comparisons among processors and (b) avoid dominant ear effects. It may not be possible to achieve both objectives for some patients and/or for some processors.

For our first direct comparison, we shall consider the same processor, but *without* precise synchronization between pulses on the two sides. This is accomplished by introducing a small difference in rate -- 10 to 15 p/s out of about 1000 p/s, and the results are displayed in Figure 19.

Special note for readers who have access to a browser with JAVA capabilities: In the HTML version of this document , whenever a *"Compare with*" note is included in the caption of one of the following Figures, the corresponding comparison Figure can be substituted instantly in the same location simply by placing the mouse cursor over that location. Removing the cursor from the location will restore the Figure. Figure 19, which immediately follows this note, is the first one having such capabilities. The html version of this document is available at http://www.rti.org/capr/qpr12a/qpr12a.html.

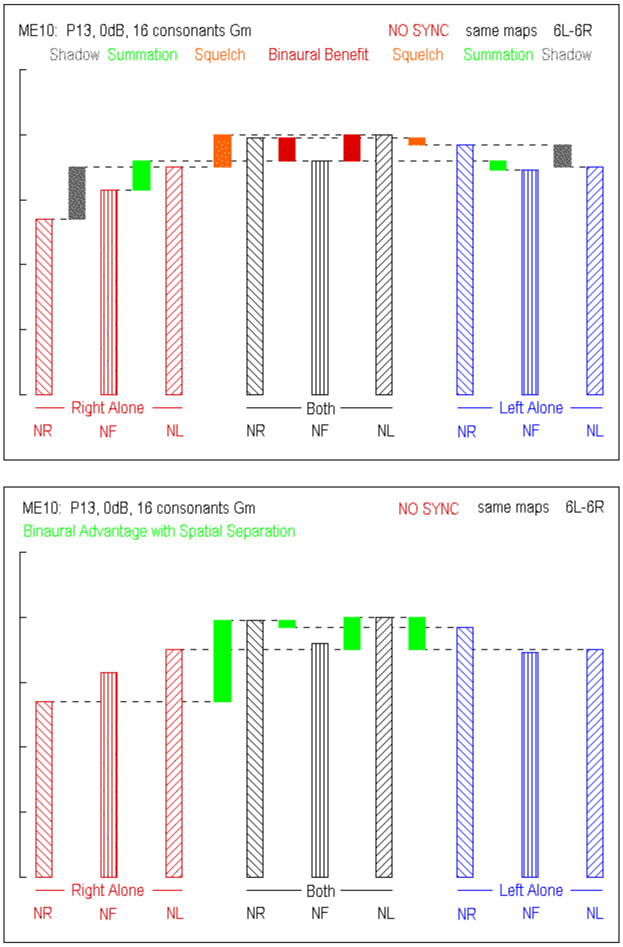


Figure 19. Consonant recognition data for the same subject (ME10): CIS processor: 6 channels Left, 6 channels Right; no synchronization of pulses between the two sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below). *Compare with Figure 18*, which is the same except that it does include pulse synchronization between the two sides.

In this case the binaural advantage may not be quite as great in the absence of precise synchrony between sides, bit it is a subtle difference.

Since the left ear alone seemed less sensitive to the impact of noise than the right, we were led to try using different mapping law exponents for the two sides. The results are shown in Figure 20.

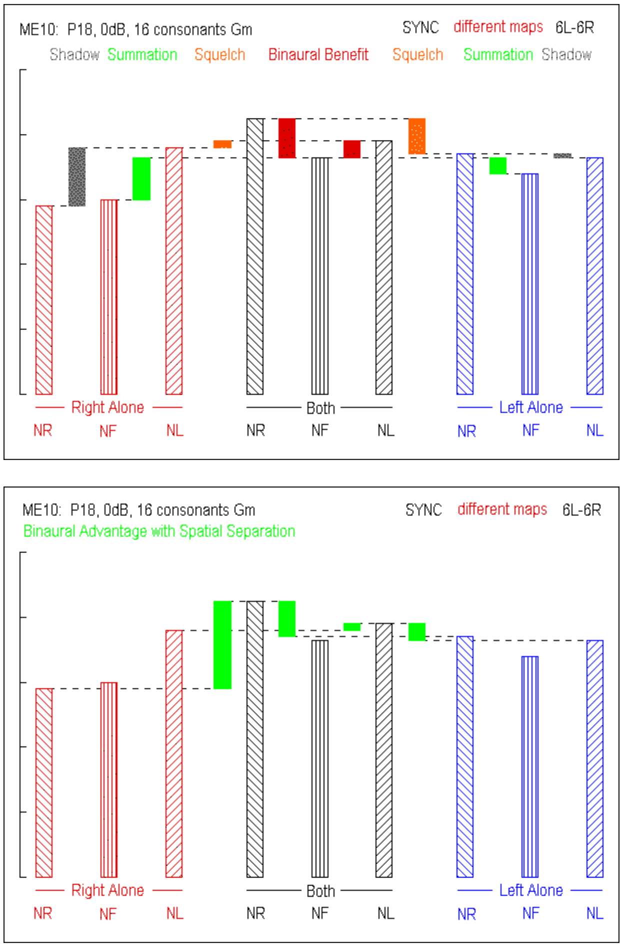


Figure 20. Consonant recognition data for the same subject (ME10). Use of different map exponents for the two sides. CIS processor: 6 channels Left, 6 channels Right; with synchronization of pulses between the two sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below). *Compare with Figure 18*, which is the same except that it uses identical map exponents for the two sides.

The performance was better for that configuration, except for a large drop in the noise front condition for the right ear alone. Note that among our three alternative analysis schemes, only the full 9-measurement assessment monitors the noise front conditions.

Would performance be better if there were more analysis and stimulation channels on each side? In Figure 21 we show the results of increasing the number of channels to 8.

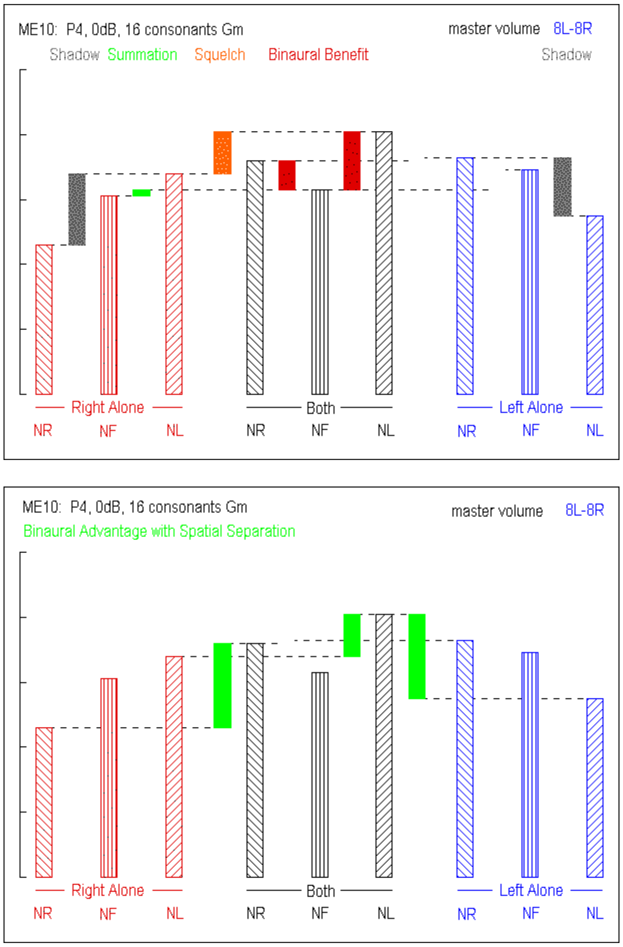


Figure 21. Consonant recognition data for the same subject (ME10). CIS processors: 8 channels Left, 8 channels Right; without synchronization of pulses between the two sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below). *Compare with Figure 19*, which is the same except that it uses only 6 channels on each side.

In this case, left ear performance is poorer than with only 6 channels.

Staying with 8 channels per side for comparison purposes, however, we now look for any performance sensitivity to relative presentation levels between the two ears. Our standard practice is to set processor master gain levels to achieve speech most-comfortable loudness (MCL) while listening with both left and right ears simultaneously. As a check, we tried setting each side's processor loudness to MCL in isolation, and then using those settings when the sides were combined. Performance data for that case are summarized in Figure 22.

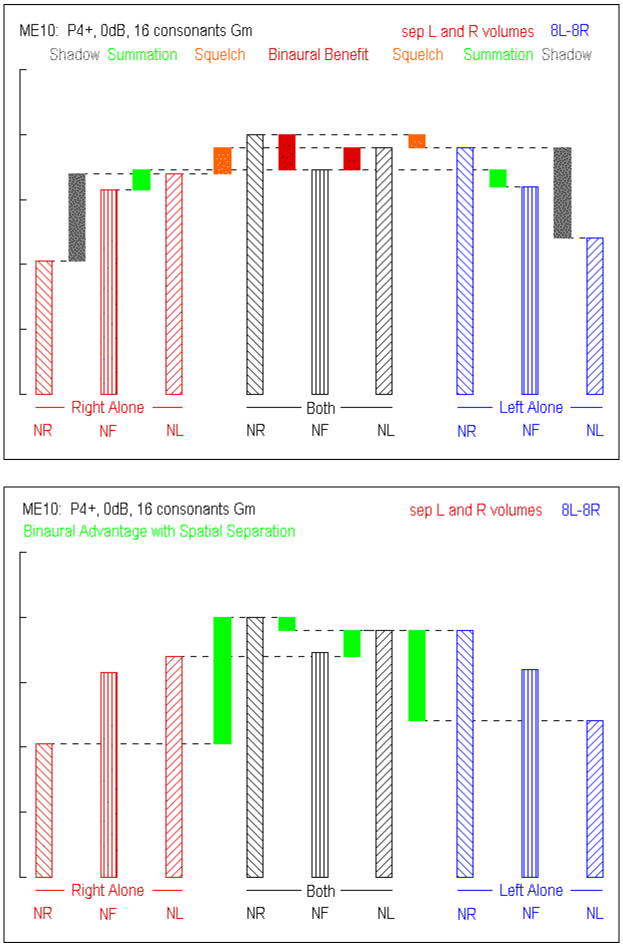


Figure 22. Consonant recognition data for the same subject (ME10). MCL gain settings determined separately for each side. CIS processors: 8 channels Left, 8 channels Right; without synchronization of pulses between the two sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below). *Compare with Figure 21*, which is the same except that a single bilateral master gain was used to set speech MCL.

While there are some differences, there certainly is nothing dramatic. As a further check, we tried mixing the two approaches -- using the right side volume setting determined unilaterally with the left side setting determined by listening to speech with both sides on. Figure 23 shows the results.

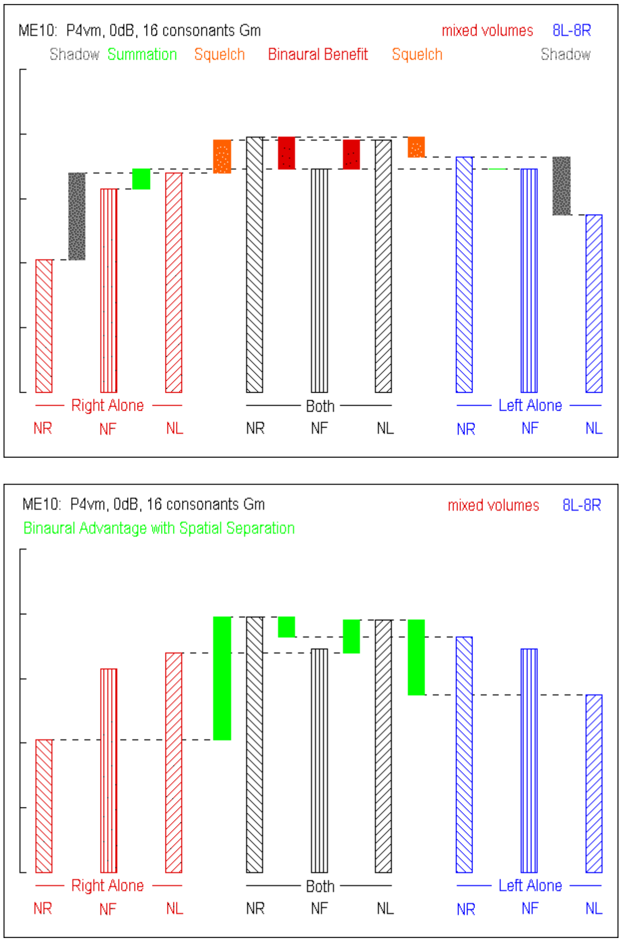


Figure 23. Consonant recognition data for the same subject (ME10). Right side MCL set to unilaterally determined value, Left side MCL corresponding to bilateral master gain MCL. CIS processors: 8 channels Left, 8 channels Right; without synchronization of pulses between the two sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below). *Compare with Figure 21*, which is the same except that a single bilateral master gain was used to set speech MCL for both sides.

Again, there is little difference to be seen. Our relatively simple binaural master gain technique does not seem to be inferior to other approaches for setting MCL levels. (A concern has been raised about possible benefits from binaural summation of loudness being misinterpreted as an advantage of bilateral stimulation. For these tests and this subject, no clear difference is observed between conditions that would produce any loudness summation effects and those that would not.)

The subject whose performance data we have been considering thus far -- ME10 -- has 11 pitch-distinct electrodes available on the left side, as indicated in Table 1 and Figure 1 above. A question of obvious interest is whether his performance might improve if all of them were utilized. The answer may be found in Figure 24.

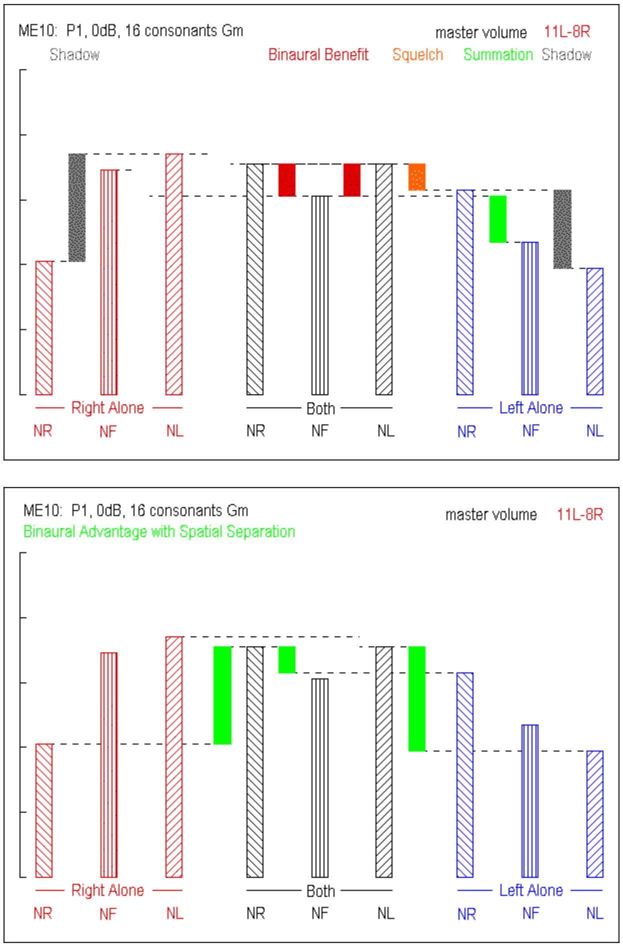


Figure 24. Consonant recognition data for the same subject (ME10). CIS processors: 11 channels Left, 8 channels Right; without synchronization of pulses between the two sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below). *Compare with Figure 21*, which is the same except that only 8 channels were used on the Left.

This performance is poorer than for either 8 channels on each side (Figure 21) or 6 on each side (Figure 19). The use of all available electrodes is not always the best decision. In fact, the left ear performance has declined enough to make the right ear dominant in this case. Note that a simple 3-measurement Binaural Benefit assessment alone would not reveal the dominant ear, while the Binaural Advantage with Spatial Separation display would.

All speech in noise data discussed so far in this report have been from a single subject, part of the fruits of one recent visit. A few additional comparisons involving different subjects may be of interest.

Figure 25 displays data for subject NU7 using bilateral Nucleus 24 clinical processors, each examining 8 spectral maxima.

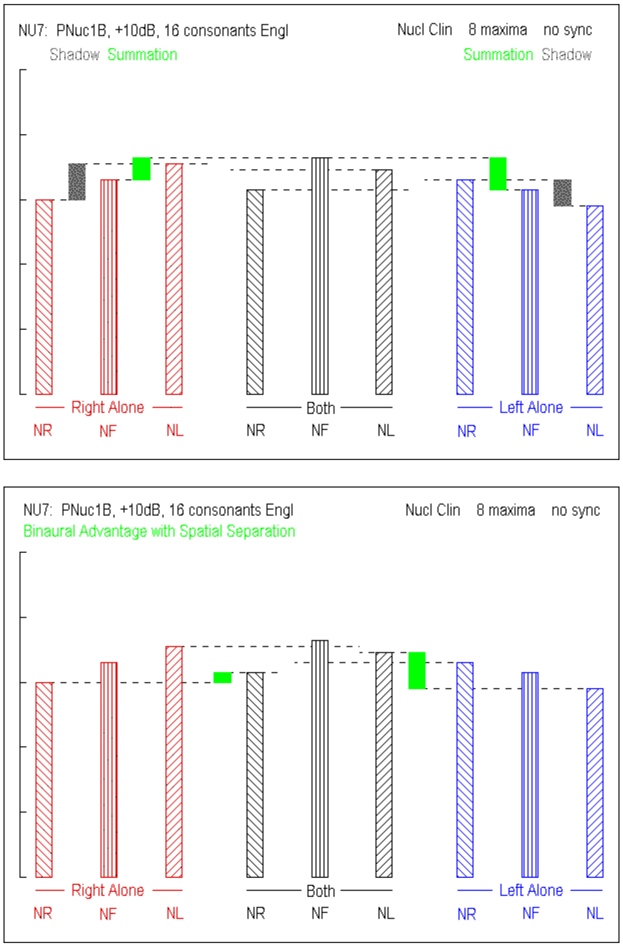


Figure 25. Consonant recognition data for subject NU7. Nucleus 24 clinical processors, each examining 8 spectral maxima. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below).

Strong summation effects lead to the highest score being for noise front with both processors.

Figure 26 shows the same subject's performance with a CIS processor delivering synchronized pulses to 6 channels on each side.

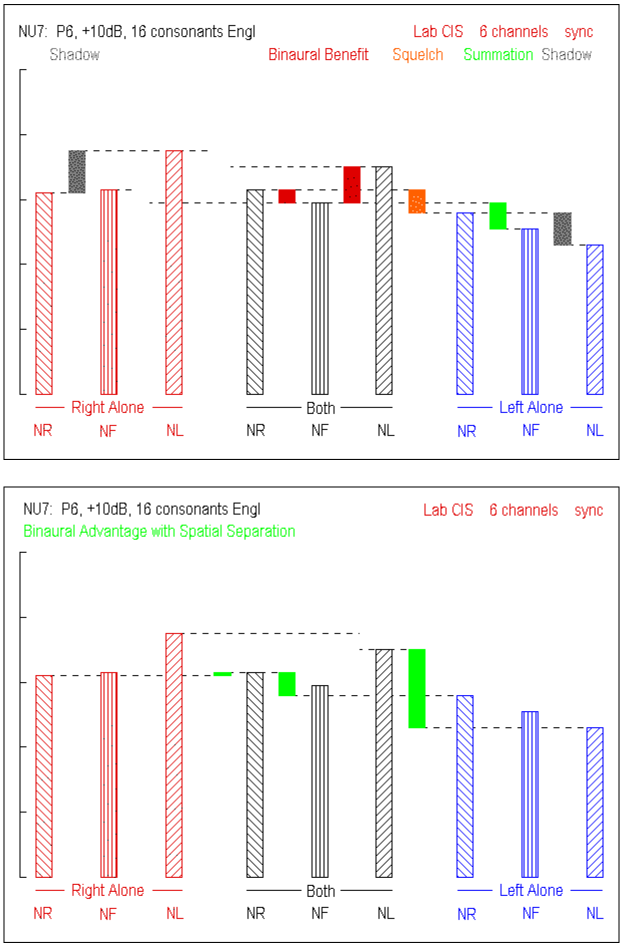


Figure 26. Consonant recognition data for the same subject (NU7). CIS laboratory processor, 6 channels Left, 6 channels Right; with synchronization of pulses between the two sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below). *Compare with Figure 25*, which is the same except for use of Nucleus 24 clinical processors.

Use of the CIS processor achieves binaural benefit for NU7, but largely by making the "noise front, both processors" performance poorer. Also among the consequences is a dominant right ear, which again is detected by the 6-measurement Binaural Advantage with Spatial Separation analysis as well as by the full 9-measurement assessment.

The data in Figure 27 are for subject ME7, with independent clinical Combi-40+ processors implementing 8-channel CIS on each side.

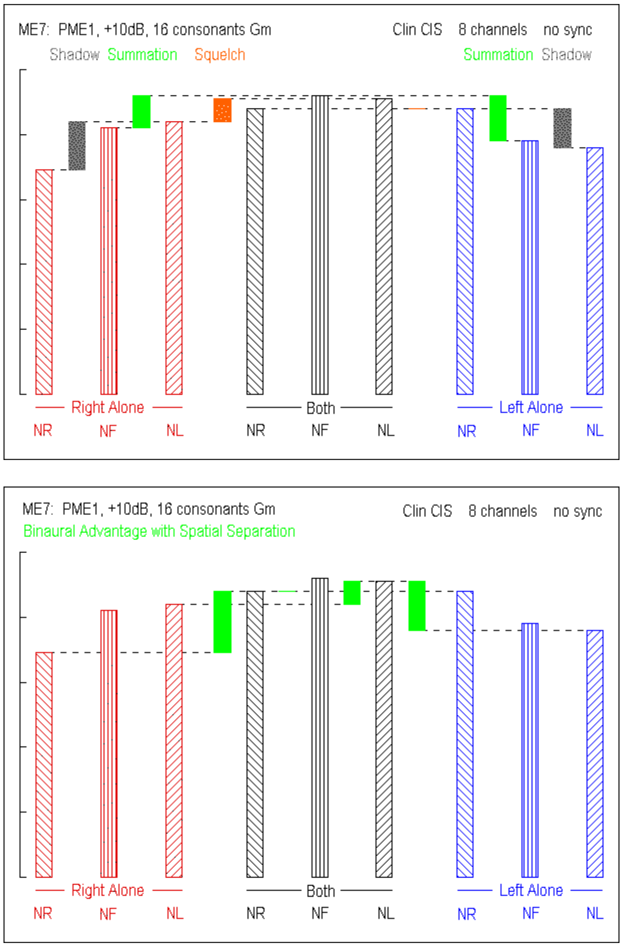
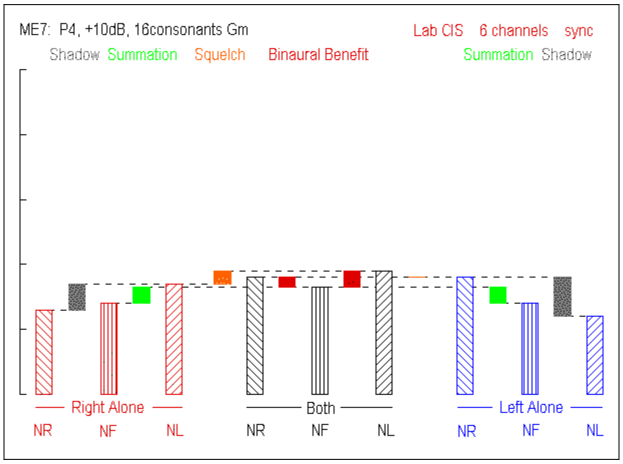


Figure 27. Consonant recognition data for subject ME7. Clinical Combi-40+ CIS processors: 8 channels Left, 8 channels Right; without synchronization of pulses between sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below).

While there is no Bilateral Benefit, there is substantial Binaural Advantage when Spatial Separation is available.



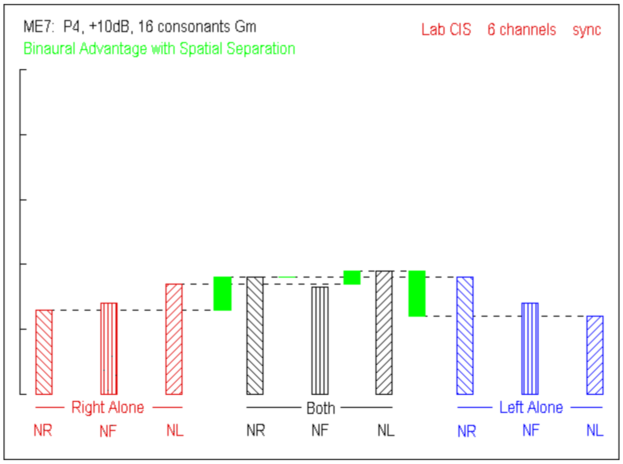


Figure 28. Consonant recognition data for the same subject (ME7). Laboratory CIS processor: 6 channels Left, 6 channels Right; with synchronization of pulses between the two sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below). *Compare with Figure 27*, which represents clinical CIS processors with 8 channels on each side and no synchronization.

As seen in Figure 28, a laboratory CIS processor with 6 channels on each side and synchronized pulses does produce a nice demonstration of binaural advantage for this subject, but he is not likely to prefer it! Binaural advantage is not everything: overall performance level matters too.

Notice also that here the extra two channels per side do help overall performance (to a highly unusual degree), and that the pattern of Binaural Advantage in the presence of Spatial Separation is quite similar across the two processor designs despite the large difference in overall performance level.

Finally, we include a series of processors for a subject (ME8) with a short Med-El array on one side and the standard Combi 40+ on the other. When fitted in a standard way, as shown in Figure 29, he exhibits a dominant left ear.

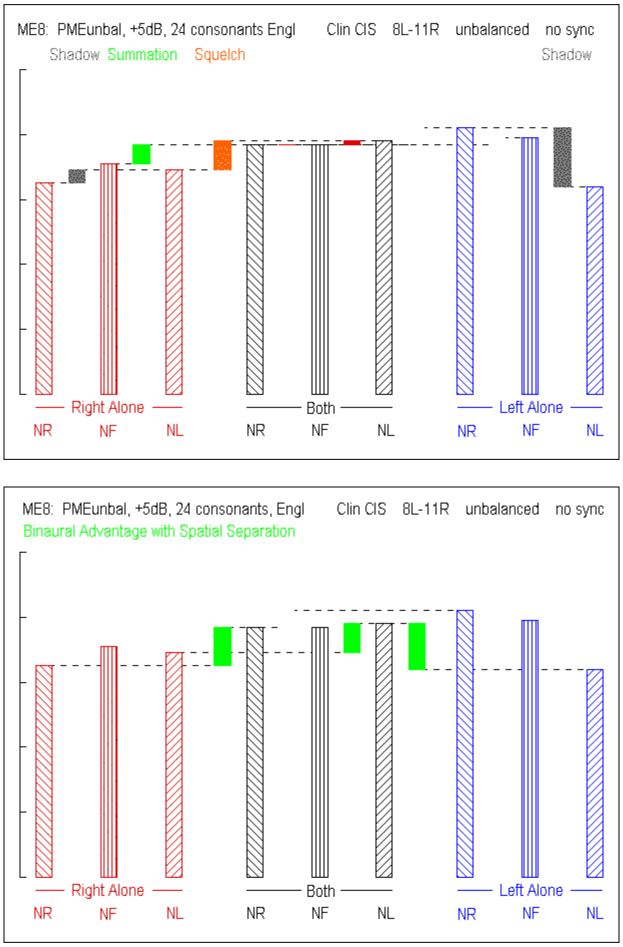
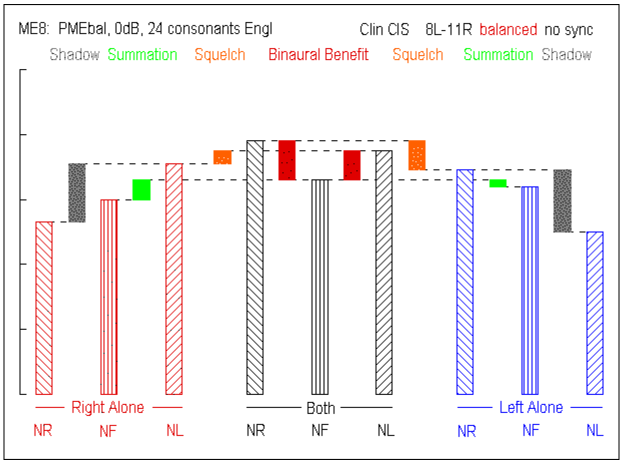


Figure 29. Consonant recognition data for subject ME8. Normal fitting of clinical CIS processors: short array Combi 40 with 8 channels Left, standard array Combi 40+ with 11 channels Right; without synchronization between sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below).

When he is allowed to "balance" the channel MCLs ("balance" is his term) in a way he prefers, left ear alone performance is damaged as displayed in Figure 30.



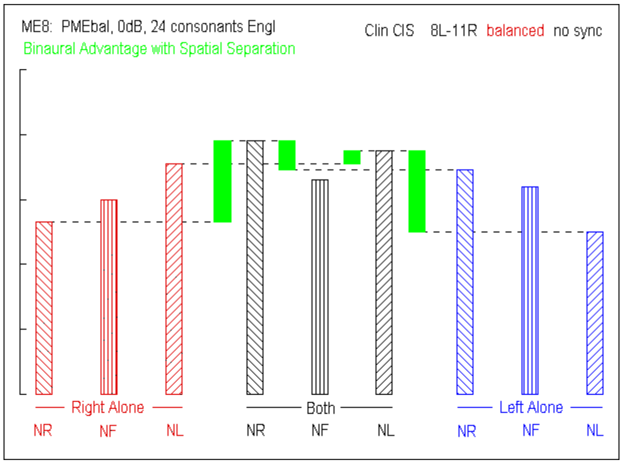


Figure 30. Consonant recognition data for the same subject (ME8). Clinical CIS processors "balanced" to patient's preference: short array Combi 40 with 8 channels Left, standard array Combi 40+ with 11 channels Right; without synchronization between sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below). *Compare with Figure 29*, which is the same except without the preferred "balancing."

But the subject's "balancing" does achieve a very nice overall picture, including a Binaural Benefit.

Next, in Figure 31, we compare a laboratory CIS processor that preserves his "balancing" but uses 8 channels on each side and synchronizes pulses across the sides.

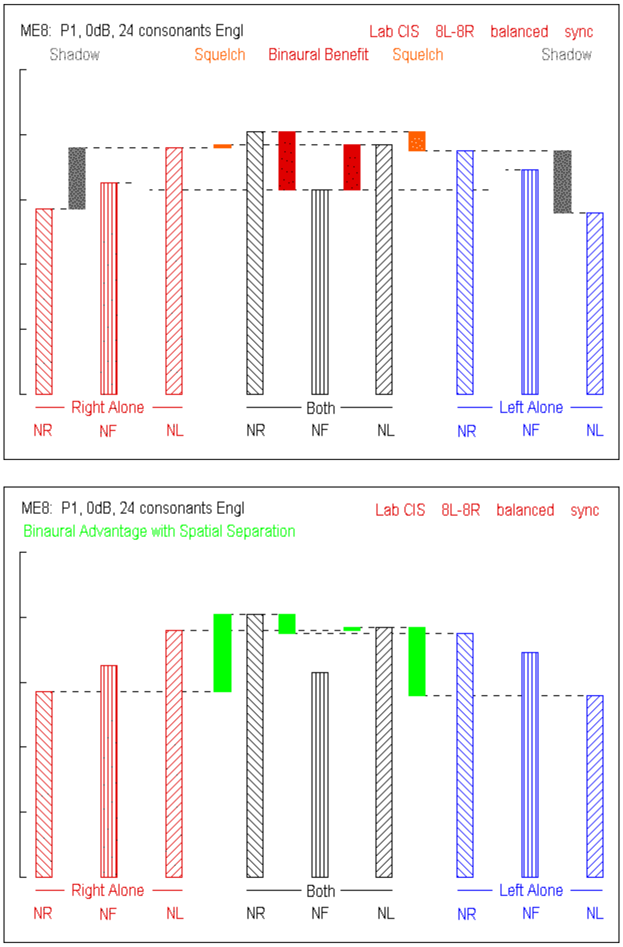


Figure 31. Consonant recognition data for the same subject (ME8). Laboratory CIS processor: 8 channels Left, 8 channels Right, with the patient's preferred "balancing" and with synchronization of pulses between the two sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below). *Compare with Figure 30*, which uses the "balanced" clinical processors with 11 channels on the Right and no synchronization.

Performance for this configuration is a bit better still.

Finally, as a check, we compare an otherwise identical laboratory processor without synchronization.

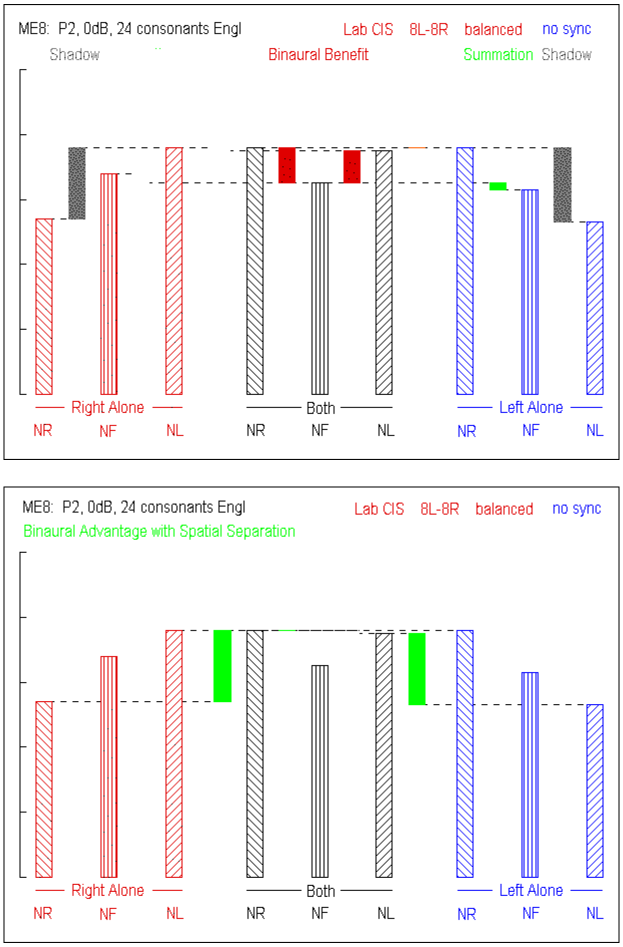


Figure 32. Consonant recognition data for the same subject (ME8). Laboratory CIS processor: 8 channels Left, 8 channels Right; with the patient's preferred "balancing" but without synchronization of pulses between the two sides. Summary of contributions to binaural effects (above) and Binaural Advantage with Spatial Separation (below). *Compare with Figure 31*, which is the same except that it does provide pulse synchronization between the two sides.

Performance with the independent processors is not, in this case, quite as good as with precise pulse synchronization across the two sides. As in other cases where we have seen this pattern, the benefit of synchronization *per se* seems to be relatively modest.

* * *

In summary, we now have in place a rather mature set of tests and procedures and a considerable collection of pilot data regarding the performance and potential of binaural cochlear implants. Our plans for future work in this area include administration of an identical battery of psychophysical and speech reception tests to a substantial cohort of binaurally implanted subjects.

In the area of binaural psychophysics we shall place high priority on studies designed to test various hypotheses regarding some of our subjects' surprising abilities to lateralize on the basis of very small

ITDs between 50 p/s stimuli input to CIS processors.

While the prospect of needing only three speech reception measurements is tempting, there are clear dangers to relying solely on Bilateral Benefit to assess and compare processor performance in directional speech spectrum noise. A detailed assessment of head shadow, summation, and squelch effects as well as Bilateral Benefit --while requiring a daunting nine measurements in each case -- yields the most insight. As a compromise, assessment of Binaural Advantage in the presence of Spatial Separation requires only six measurements and provides sensitivity to dominant ear effects and most of the other important situations that can be missed by a 3-measurement protocol. Only the full 9-measurement approach detects differences in unilateral performance with noise from the front, however, and as demonstrated by the cases we have examined in this report such differences, while relatively rare, can be dramatic in their magnitudes. We plan to make judicious use of 6-measurement sets as an efficient screening mechanism in our search for better processing approaches, but to continue to document reference processors and the most promising alternatives with the full 9-measurement assessment.

III. Plans for the next quarter

Our plans for the next quarter include the following:

- Preparation for, and participation in, the *32nd Annual Neural Prosthesis Workshop*, to be held in Bethesda, MD, Oct. 17-19.
- Further development of new processing strategies designed to provide a closer mimicking of normal auditory functions.
- Initial development of Access databases for psychophysical and evoked potential studies (these databases will be similar in design to the database already developed for speech processor studies, see QPR 10 for the current contract).
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication, including the two invited chapters mentioned in the Introduction to this report.
- Possible studies with recipients of bilateral cochlear implants (studies had been scheduled but were cancelled by subjects following news of the tragedy of September 11, discouraging air travel at least for a while by anyone).
- Possible studies in return visits by local subjects.

IV. Acknowledgments

We thank volunteer research subjects NU4, NU5, NU6, NU7, NU8, ME2, ME3, ME4, ME5, ME7, ME8, ME9, and ME10 for their generosity and good humor. We also are grateful to their implant surgeons and audiological caregivers -- from Durham, NC; Iowa City, IA; Würzburg, Germany; Manchester, England; Innsbrück, Austria; and Vienna, Austria -- for referrals, advice, and assistance.

Appendix 1. Summary of reporting activity for this quarter

Reporting activity for this quarter, covering the period of July 1 through September 30, 2001, included the following:

Invited Talks

Brill SM, Lawson DT: Psychophysics of simultaneous electric and acoustic stimulation. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 19-24, 2001. (p. 34 in the book of Abstracts)

Lawson DT, Brill SM, Wolford RD, Schatzer R, Wilson BS: Speech processors for binaural stimulation. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 19-24, 2001. (p. 24 in the book of Abstracts)

Tyler RS, Preece JP, van Hoesel R, Parkinson AJ, Rubinstein JT, Gantz BJ, Wolaver AP, Wilson BS: Preliminary speech perception and localization experiments involving binaural cochlear implants. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 19-24, 2001. (p. 22 in the book of Abstracts; Wilson's participation in this work was supported jointly by the present project and by the Program Project Grant on Cochlear Implants at the University of Iowa)

Wilson BS, Brill SM, Cartee LA, Lawson DT, Schatzer R, Wolford RD: Some likely next steps in the further development of cochlear prostheses. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 19-24, 2001. (p. 47 in the book of Abstracts)

Brill SM: Binaural psychophysics. *Med-El US Investigator's Meeting*, Quebec City, Canada, July 20-21, 2001.

Lawson DT: Improving CIS processor fittings. *Med-El US Investigator's Meeting*, Quebec City, Canada, July 20-21, 2001.

Session Chair

Brill SM: Moderator. Session on Signal Processing for Implants II. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 19-24, 2001.

Publication

Tyler RS, Parkinson A, Wilson BS, Parkinson W, Lowder M, Witt S, Gantz B, Rubinstein J: Evaluation of different choices of *n* in an *n*-of-*m* processor for cochlear implants. Adv Oto-Rhino-Laryngol 57: 311-315, 2000. (Wilson's participation in this work was supported jointly by the present project and by the Program Project Grant on Cochlear Implants at the University of Iowa.)

Additional Presentation

Cartee LA, Finley CC, Wilson BS: A model of the intracochlear evoked potential. *2001 Conference on Implantable Auditory Prostheses*, Pacific Grove, CA, August 19-24, 2001. (p. 82 in the book of Abstracts; this work was supported jointly by the present project and Dr. Cartee's separate NIH project, on "Development of a Cochlear Neuron Electrophysiology Model")