Second Quarterly Progress Report

July 1 through September 30, 2002
NIH Project N01-DC-2-1002

Speech Processors for Auditory Prostheses

Prepared by

Dewey Lawson, Robert Wolford,
Blake Wilson, and Reinhold Schatzer

Center for Auditory Prosthesis Research
Research Triangle Institute
Research Triangle Park, NC

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:

- 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, who will provide engineering support for the project.
- 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.
- Preparation for studies with percutaneous subjects 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 at least four subjects.

In this report we describe recent work with bilateral subjects ME-12 and ME-16. The results from other work done this quarter will be included in subsequent reports.

II. Longitudinal studies of early performance improvements with binaural cochlear implants

Background

The vast majority of our speech reception studies over the years have involved acute comparisons of different processing strategies when used by the same subject. Occasionally, however, special circumstances and opportunities have led us to undertake longitudinal studies of performance changes with chronic use of a new processing strategy. Such past studies have included subjects implanted with a percutaneous version of the Nucleus electrode array [see QPRs 1 and 3 for project N01-DC-5-2103] and subjects followed for several years after beginning to use Med-El CIS-Link processors with their percutaneous Ineraid implants [see QPRs 2 and 4 for project N01-DC-8-2105].

Having observed that certain processing strategy attributes which once severely limited performance by a particular subject in acute comparisons later were found to enhance performance in the same subject, we currently are revisiting comparisons that revealed dramatic differences in performance at an earlier stage in our subjects' clinical experience. Among the hypotheses motivating such studies is that some subjects may perform better with strategies that convey a relatively limited amount of information in their early experience, whereas at a later stage the presentation of additional information is needed for optimal performance. One possibility is that such subjects are better served by a learning or acclimatization period with the limited processor before beginning long-term use of a processor supplying more information. Alternatively, such subjects might learn to make use of the additional information more rapidly if given that information from the outset. We expect to present data in future reports that will address these possibilities.

Among the 17 bilaterally implanted subjects we have studied in recent years, seven have returned for one or more additional visits, allowing us opportunities for some longitudinal comparisons. Two of the latter subjects were implanted quite recently and also live close enough to our laboratories for relatively frequent, brief visits. These advantages have allowed more extensive longitudinal comparisons with those two subjects, including comparisons over the initial period of implant use, which is the period of the greatest improvement in speech reception scores for most unilateral implant patients.

The focus of this report is on the longitudinal studies conducted to date with the local and recently-implanted subjects ME-12 and ME-16. Those studies have included measures of speech reception in noise using a (separate) fixed processor for each subject at multiple points in time following the implant. The studies with the other five subjects who returned for repeat visits to the laboratories did not include such measures, as either other measures took precedence or our facilities for measuring speech recognition in the presence of directionally-distinct noise were not yet available.

Subjects

Subject ME-12 received his bilateral implants at the University of North Carolina hospitals in Chapel Hill (UNC-CH) at age 56. He had a strong family history of hearing loss, and a personal history of noise exposure during his 20-year military career. Since retirement from military service he had done consulting work and administration. He was first diagnosed with hearing loss at age 42 and began using an ITE aid in the right ear at that time. A left hearing aid was added three years later and use of BTE devices began at age 55. Use of an aid on the right side was abandoned 7 months before implantation, and he had been without binaural cues for 19 months prior to first fitting of his Tempo+ devices. He reported bilateral tinnitus before and after implantation, but a definite lessening of dizziness and balance problems after the surgery. His own assessment of his hearing one month after first fittings was that his performance with the left ear alone was better than with the right alone and that use of both processors was better than the use of either alone. The left ear was preferred for telephone conversation. His everyday practice was to use both devices all the time, and he reported the ability to recognize regional accents, to learn differences among individual speakers' voices quickly, and to detect the direction from which birdsong, automobile noise, hammering, and other construction sounds came. He volunteered, however, that he could not judge the distance of sound sources.

Subject ME-16's hearing loss is of unknown etiology (the only family history is her mother's loss post age 60). It was first documented as a severe high frequency loss at age 30, and categorized as profound by age 33. She received bilateral Combi 40+ implants from UNC-CH at age 41, after 9 years' use of bilateral hearing aids. She reported that she had experienced tinnitus before implantation, that it had been very loud between the surgery and initial programming of her implanted devices, and that she had noticed it only once or twice since -- and only when the devices were turned off. She denied any history of dizziness. Her own assessment one month after initial fitting was that her speech reception performance was better with the right ear alone than with the left alone, and best with both. Emphasizing the brevity of her experience with the devices as of that time, she reported having noticed an awareness of which direction a train was approaching from and had, in an informal test, correctly identified the direction from which her daughter spoke to her in two of three trials.

Based on the availability of these two local subjects beginning quite early in their experience with binaural cochlear implants, and performance results for ME-12 over his first few months experience, we decided to plan a formal longitudinal study.

Studies

A particular processor was chosen for repeated use in evaluating longitudinal performance changes with ME-12 and ME-16. The serial number assigned to that processor was 1 in the case of both subjects. The processors differ only in the currents assigned to threshold and maximum (MCL) stimulation levels for each of the 12 electrodes in each of the two arrays for each of the two subjects.

The bilateral processors have stereo inputs and stimulate the 12 electrodes on each side synchronously. A 1st order high pass filter attenuates signal components below 1.2 kHz. Each electrode is associated, in tonotopic order, with the output of a 6th order bandpass filter, with the 12 filters spanning an overall analysis frequency range of 350 to 5500 Hz in logarithmically equal bands. The output for each band is detected using full-wave rectification followed by a 4th order, 200 Hz low-pass smoothing filter. The mapping law determining stimulus current amplitudes has an exponent of -.0001 in every case. (The form of the mapping law is: Output current amplitude = A * (envelope signal)^{exponent} + k, where A and k are adjusted so that the minimum current amplitude corresponds to auditory threshold and the maximum current amplitude corresponds to a percept at most comfortable loudness.) Our bench processing hardware provides appropriate signals for transcutaneous control of each subject's implanted C40P stimulating electronics. On each side, the processor instructs the implanted device to deliver 26.7 μs/phase balanced biphasic pulses at the rate of 1515/s to each electrode in a staggered order of stimulation (1,7,2,8,3,9,4,10,5,11,6,12).

The processors we are using for our longitudinal comparisons differ from the clinical processors the subjects use every day in at least two respects: (1) the clinical devices analyze an overall frequency range extending up to 7 kHz rather than the 5.5 kHz upper limit chosen to make test results comparable with other data from our laboratory, and (2) parameters of the clinical processors are being adjusted periodically according to the judgment of the clinical caregivers.

ME-16 is enrolled in a clinical study at UNC-CH under a protocol that includes extensive use of the same sentence test materials we would otherwise be including in our longitudinal study. Though not enrolled in the formal clinical study, ME-12 also is being tested at UNC-CH with the same sentences, so we are avoiding use of those materials with both subjects.

Our speech testing is based on measures of the identification of 24 medial consonants in /a/-C-/a/ context, uttered by a male talker. At least ten sets of the 24 consonants are presented in each condition, the order of presentation being randomized within sets to allow statistical monitoring of measurement uncertainties. Presentation is via sound alone, and there is no feedback as to correct or incorrect results. Stereo recordings are prepared using head related transfer function (HRTF) processing to combine speech from the front with CCITT speech spectrum noise from the front, from 90 degrees to the left, and from 90 degrees to the right (see QPR 10, NIH Project N01-DC-8-2105). The HRTFs do not include ear canal effects, in order to more closely correspond to the clinical microphone signals. The recordings are presented directly to the left and right inputs of the speech processor.

Results

Results obtained to date for both longitudinal subjects are summarized in Figures 1 and 2 and in Table I. The data were obtained during the first, second, third, sixth, and seventh months post first fitting for ME-12, and in the second and third months for ME-16. The initial studies in noise with ME-12 were done at a signal-to-noise ratio of +10 dB, but in the second month after that subject's initial fitting we decided to introduce more noise in order to decrease the likelihood of ceiling effects. Contemporaneous second month and all subsequent tests with ME-12 were done at +5 dB, as were all tests in noise from the beginning with ME-16. Our plan is to continue to follow both subjects with testing at similar intervals. At selected points in the longitudinal studies with our fixed processor designs, we also plan to compare performance using otherwise identical processors that utilize the overall frequency range and/or adjusted thresholds and maximum stimulation amplitudes of each subject's evolving clinical processors.

Between the first and second months after the first fitting of his cochlear implants as shown in Figure 1, ME-12's performance showed substantial improvement for all three directions of noise incidence at a SNR of +10 dB. During his visit in the second month, contemporaneous measurements also were obtained for +5 dB, the SNR chosen for subsequent longitudinal comparisons. Scores for all three noise directions were somewhat higher, but not significantly so, in month 3, but were significantly lower when the next tests were done in month 6. The most recent results, from month 7, don't differ significantly from the highest scores of month 3.

ME-16's results demonstrated a similar early improvement between the second and third months after first fitting. The change was particularly striking for the condition in which noise and speech came from the same direction (NF).

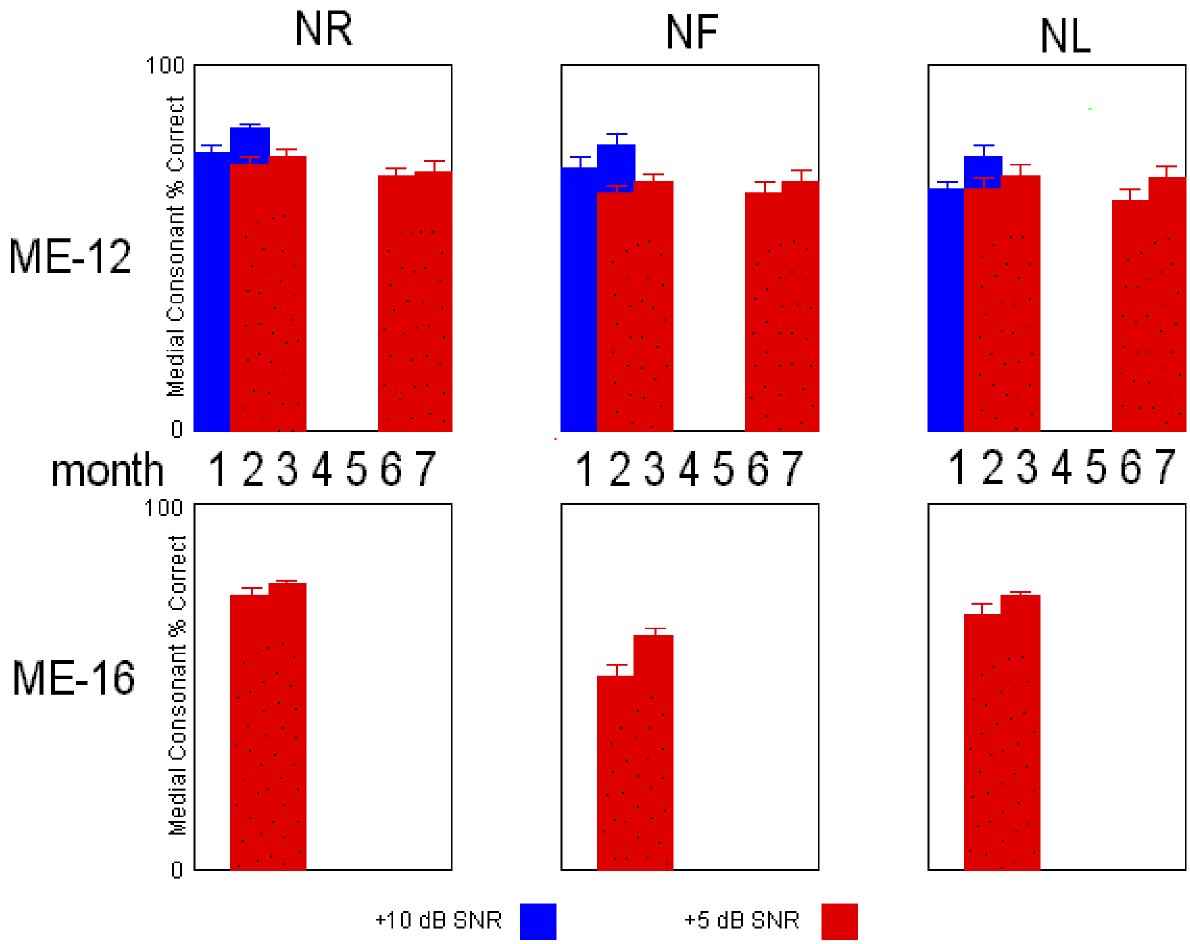

Figure 1. Identification of medial consonants in the presence of directional speech spectrum noise as a function of duration of cochlear implant use. Bars in each panel plot percent correct medial consonant identification scores *vs.* number of months since first fitting. The height of each panel corresponds to 100 % correct. Upper row data are for subject ME-12 and lower row data for subject ME-16. The three columns contain data for speech from the front combined with noise from the right (NR), the front (NF), and the left (NL), respectively. Both ears were stimulated in every case. Early data for ME-12 with a signal-to-noise ratio (SNR) of + 10 dB are shown in blue, while the bulk of the data, shown in red, are for a SNR of +5 dB. Error bars indicate standard deviation of the mean.

Figure 2 displays the same data, but grouped to highlight any changes in noise direction effects over the months.

In Figure 2, we see that ME-12's results for the first month indicate a dominant left ear, with performance for noise from the front being intermediate to superior performance when noise came from the right and inferior performance when the noise came from the dominant left side.

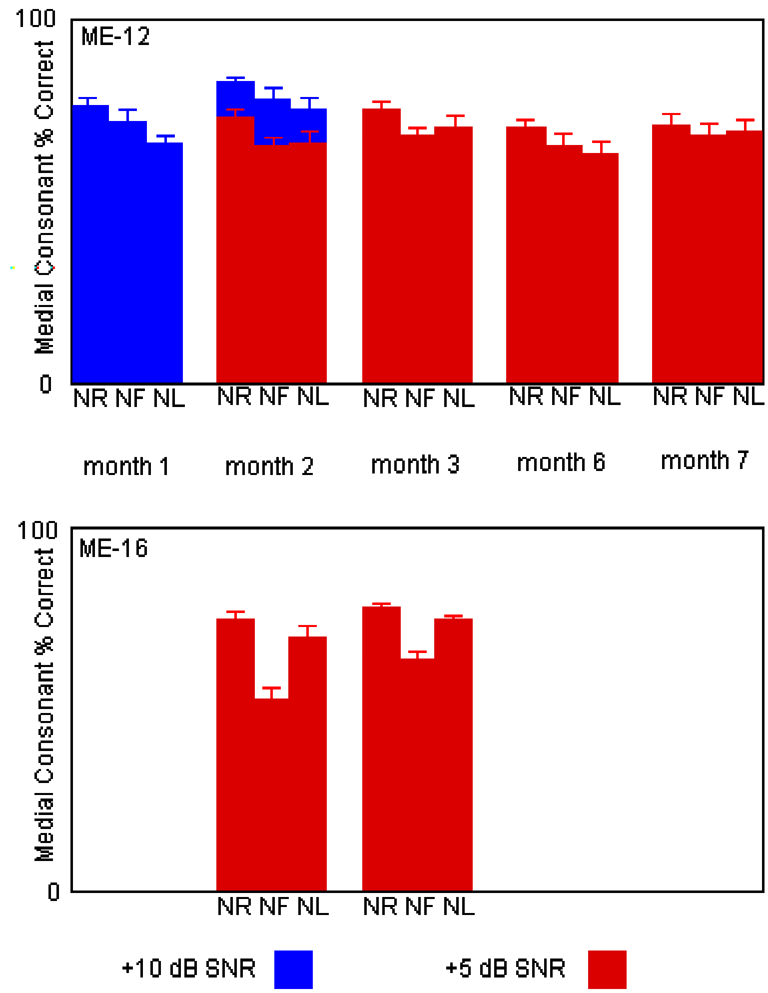

Figure 2. Identification of medial consonants in the presence of speech spectrum noise, as a function of the directions from which noise and speech come, at various times after first fitting of binaural cochlear implants. Each group of three bars shows percent correct medial consonant identification scores for speech from the front combined with noise from the right (NR), the front (NF), and the left (NL), respectively. Both ears were stimulated in each case. The height of each panel corresponds to 100 % correct. Upper panel data are for subject ME-12 and the lower panel data for subject ME-16. The comparisons for each subject are displayed in chronological order, from one to seven months after first fitting. Early data for ME-12 with a signal-to-noise ratio (SNR) of + 10 dB are shown in blue, while the bulk of the data, shown in red, are for a SNR of +5 dB. Error bars indicate standard error of the mean.

The left dominance effect appears somewhat less in the data from month 2, where NL and NF performance do not differ significantly. That trend seems to have continued through the subject's visit in month 3, with NR performance even less superior -- but still significantly so -- to that under NL conditions, in a context of improved overall performance. ME-12's status at that point (month 3) regarding speech in directionally-controlled noise is explored in greater detail below in the discussion surrounding Figure 3.

The data in Figure 2 from month 6 suggest a step backward for ME-12 in the pattern of noise direction effects as well as in absolute performance levels.

By the seventh month, not only were overall levels essentially restored to their higher values, but there was no longer any significant difference in performance as a function of noise direction. No sign of left ear dominance remained.

Table I. Longitudinal Results: Medial Consonant Recognition in Speech Spectrum Noise, Both Ears Stimulated

Subject	S/N Ratio	Month		Noise Right	Noise Front	Noise Left
ME-12	+10 dB	1		76 ± 2	72 ± 3	66 ± 2
		2		83 ± 1, 82 ± 2	73 ± 2, 78 ± 3	75 ± 3, 73 ± 2
	+5 dB	2		73 ± 2	65 ± 2	66 ± 3
		3		75 ± 2	68 ± 2	70 ± 3
		6		70 ± 2	65 ± 3	63 ± 3
		7		71 ± 3	68 ± 3	69 ± 3
ME-16	+5 dB	2		75 ± 2	53 ± 3	70 ± 3
		3		78 ± 1	64 ± 2	75 ± 1

ME-16's data at two months demonstrate a robust binaural benefit, in that performance was substantially better when the noise direction was different from that of the speech, to either side. There also was a significant difference in scores between NR and NL conditions, consistent with greater reliance on the right ear.

By month 3, ME-16's performance had improved significantly for noise from the left and especially for noise from the same direction as the speech. While the binaural benefit appeared to be less, overall performance in the presence of noise had improved considerably. The trend for ME-16 at the three month point seems to be consistent with the one that led to ME-12's lack of any significant noise direction effect by month 7.

A full set of nine measurements was made during the month 3 visit of ME-12, evaluating performance in NR, NF, and NL conditions for right ear and left ear alone (RE and LE) as well as for both ears (BE). While very expensive in testing time, such a set of measurements supports a much more detailed understanding of the roles of various mechanisms associated with the decoding of speech in noise, with and without distinct angles of incidence for the two. The nine measurements, made at a SNR of +5 dB, are repeated in each of the three panels of Figure 3. Each panel illustrates a distinct type of analysis based on differences among the nine measured values.

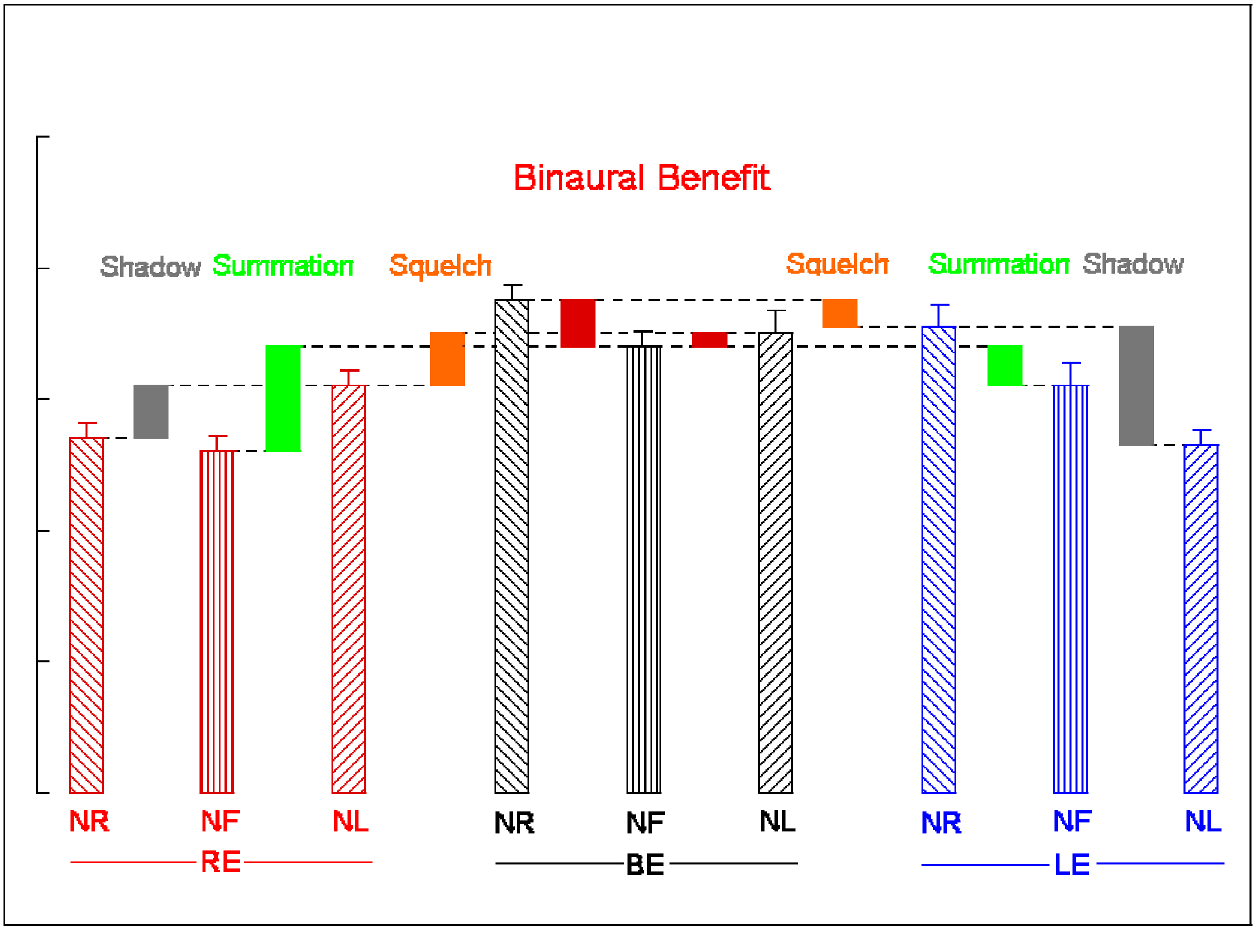

Figure 3, Panel 1 *(continued on next page)*

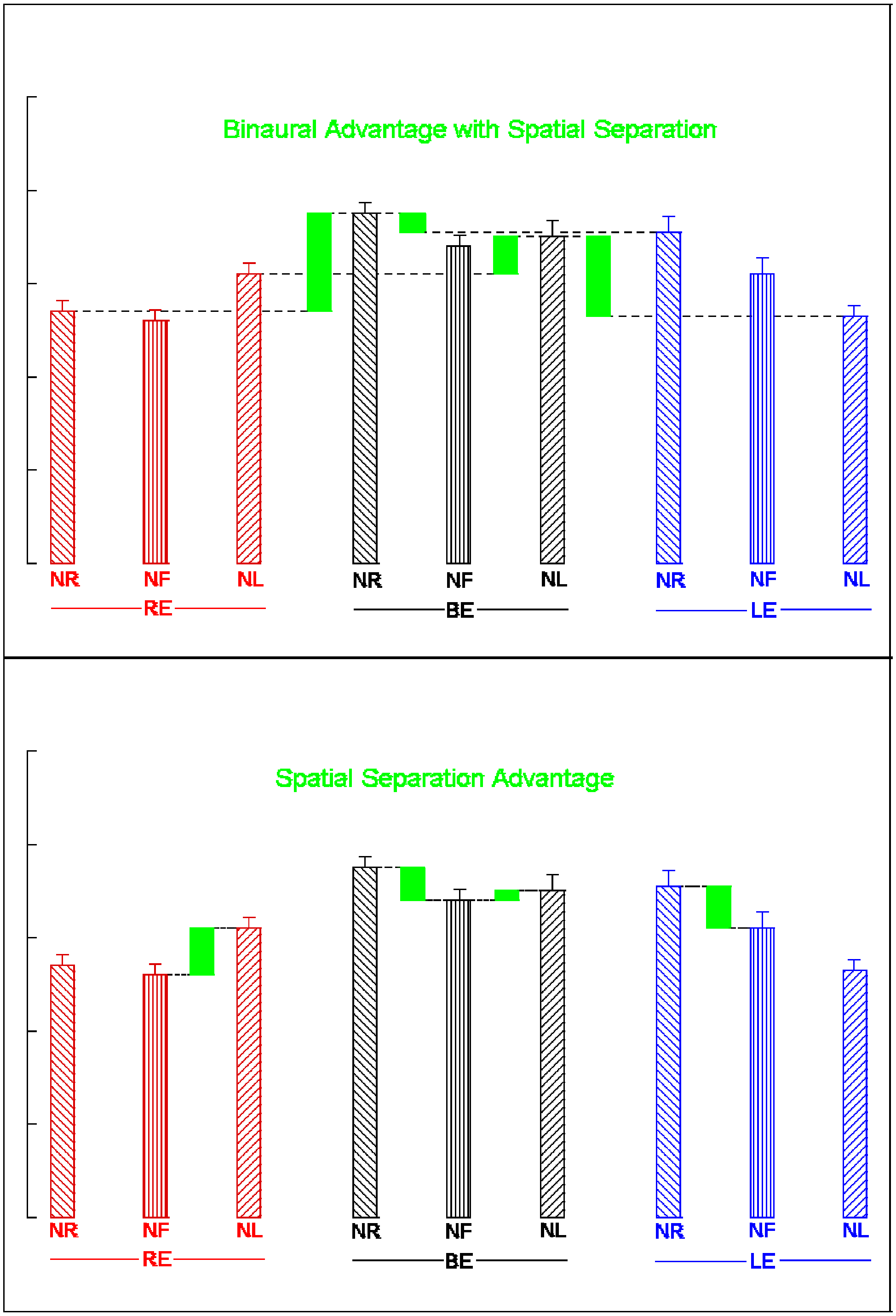

Figure 3, Panels 2 and 3. Identification of medial consonants in the presence of speech spectrum noise, as a function of the directions from which noise and speech come; subject ME-12, three months after first fitting of binaural cochlear implants. The signal to noise ratio (SNR) was +5 dB. Each group of three bars includes percent correct medial consonant identification scores for speech from the front combined with noise from the right (NR), the front (NF), and the left (NL), respectively. From left to right, the first group of bars represents performance with only the right ear stimulated (RE), the second group with both ears (BE), and the third group with only the left ear (LE). The height of the scale in each panel corresponds to 100 % correct. While the percent correct data bars shown in each of the three panels are the same, differences among various pairs of bars are highlighted in each panel to illustrate ways of interpreting the results. Each derived quantity is displayed as a difference bar and labeled. Error bars indicate standard error of the mean.

In the top panel of Figure 3, we see that each of the three mechanisms to which the special benefits of binaural hearing typically are ascribed were contributing to ME-12's performance as of month 3 -- the advantage to the **shadowed** ear when noise is from either side, the **summation** effect that can make performance with both ears better than with either ear alone when noise and signal come from the same direction, and the **squelch** effect that, for noise from the side, can make performance with both ears still higher than that possible with the shadowed ear alone. (For a more detailed discussion of these, and the other analyses shown in the lower two panels of Figure 3, see QPR 12 for NIH Project N01-DC-8-2105.)

In considering the apparent trend we have discussed for our ME-12 and ME-16 longitudinal data thus far, we note that improved utilization of summation -- with no reduction in the utilization of any other binaural cue -- could increase scores obtained with both ears and noise from the front (BE NF) and in the process appear to have reduced "binaural benefit" as assessed using the three BE conditions alone. This possibility illustrates one of the dangers of analyses based only on performance data for simultaneous use of both ears.

The Binaural Advantage with Spatial Separation analysis shown in the middle panel of Figure 3 offers an alternative to "binaural benefit," one that cannot be confounded by large summation effects.

In the bottom panel of Figure 3, the "binaural benefit" of the top panel is identified instead as the Spatial Separation Advantage when both ears are used together. Also shown are the Spatial Separation Advantages when each ear is used alone.

(For a more detailed discussion of each of the types of analysis shown in Figure 3, see QPR 12 for NIH Project N01-DC-8-2105.)

Summary

We plan to continue with the longitudinal study of these two subjects, with the next measurements for ME-16 occurring six or seven months after first fitting to match data already obtained for ME-12. Results to date seem consistent with a trend of relatively slow improvements in overall consonant recognition scores along with more rapid improvements in performance when noise comes from the same direction as speech, and reductions in performance differences across noise direction differences. Of immediate interest will be whether ME-16's next data are consistent with that trend.

III. Plans for the next quarter

Among the activities planned for the next quarter are:

- Attendance by Xiaoan Sun and Dewey Lawson, and presentation by Blake Wilson, at the 33rd annual Neural Prosthesis Workshop, October 16 - 18 in Bethesda, MD.

- Participation by Dewey Lawson in the annual Binaural Bash at Boston University, October 18 - 19.

- Invited lecture by Dewey Lawson at the annual meeting of the North Carolina chapter of the Acoustical Society of America in Raleigh, NC, November 8.

- Studies with percutaneous subjects SR-9, October 2-11, and SR3, November 4-15,including measurements of intracochlear evoked potentials and initial trials of a new speech processing strategy using nonlinearities to more faithfully mimic aspects of normal hearing.

- Studies with new bilaterally implanted subject ME-18, October 21 - November 1.

- Co-sponsorship, with Med-El Corporation, of a Hearing Preservation Workshop at the Indiana University School of Medicine in Indianapolis, November 8-10, and a presentation at that workshop by Blake Wilson.

- A visit by consultant Enrique Lopez-Poveda from Albacete, Spain, November 11-14 to collaborate on the development of a new speech processing strategy.

- A visit November 12 by colleague Arturs Lorens from Warsaw, Poland.

- One week of studies with a new European subject, ME-19, who utilizes combined electric and acoustic hearing, November 18-22.

- Two weeks of studies with another new European subject, ME-20, who also uses both electric and acoustic stimulation, December 2 - 13.

- Visits during the studies with ME-20 by colleagues Marcel Pok from Frankfurt a.M. and Jan Kiefer from Würzburg, Germany.

- Hosting a mini-symposium with Dr. Leslie Collins of the Duke University School of Engineering and several of her graduate students, on current research topics related to cochlear implants.

- Presentation by Blake Wilson at the 3rd Conference on Bilateral Cochlear Implantation and Bilateral Signal Processing, Würzburg, Germany, December 12-17.

IV. Acknowledgments

We thank volunteer research subjects ME-12 and ME-16 for their contributions to the work described in this report, and subject ME-17 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 July 1 through September 30, 2002, included the following presentations and publications:

Presentations

Wolford RD: Bilateral cochlear implants = Binaural advantage? Presented at the *Annual Meeting of the American Academy of Audiology*, Philadelphia, PA, April 18-20, 2002. (This presentation was inadvertently omitted from the Appendix on reporting activity in the prior QPR 1 for this project.)

Wilson BS: Future directions for cochlear implants. Keynote speech, *7th International Cochlear Implant Conference*, Manchester, England, September 4-6, 2002.

Cooper H, Tyler RS (moderators), Graham J, Wilson BS, Plant G, Saeed S (panelists): Panel on the future for adults. *7th International Cochlear Implant Conference*, Manchester, England, September 4-6, 2002.

Tyler RS, Gantz BJ, Rubinstein JT, Witt S, Bryant D, Wilson BS: What we have learned about binaural hearing. *7th International Cochlear Implant Conference*, Manchester, England, September 4-6, 2002.

Publications

Loeb GE, Wilson BS: Prosthetics, Sensory systems. In *Handbook of Brain Theory and Neural Networks*, 2nd edition, edited by MA Arbib, MIT Press, Cambridge, MA, 2003, pp. 926-929.

Tyler RS, Preece JP, Wilson BS, Rubinstein JT, Parkinson AJ, Wolaver AA, Gantz BJ: Distance, localization and speech perception pilot studies with bilateral cochlear implants. In *Cochlear Implants -- An Update*, edited by T Kubo, Y Takahashi and T Iwaki, Kugler Publications, The Hague, The Netherlands, 2002, pp. 517-521.