Third Quarterly Progress Report

October 1 through December 31, 2002
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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 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:

- A visit by consultant Marian Zerbi, October 4 – 8, for implementation and testing of streaming mode software for a new current source interface for use with percutaneous subjects.

- 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.

- Studies with percutaneous subjects SR9, October 2-11, and SR3, November 4-15, including measurements of intracochlear evoked potentials for "split-phase" (monophasic-like) pulses, and initial trials of a new speech processing strategy using nonlinearities to more faithfully mimic aspects of normal hearing.

- Studies with new subject ME18, implanted bilaterally with Med-El devices and using bilateral Tempo+ clinical processors, October 21 - November 1.

- Continuing studies with local subject ME16, implanted bilaterally with Med-El Tempo+ devices.

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

- 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.

- 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 Artur Lorens from Warsaw, Poland.

- One week of studies with a new European subject, ME19, who utilizes combined electric and acoustic hearing, November 18-22. This subject received partial insertion of a Med-El device on one side and uses it in conjunction with bilateral digital hearing aids.

- Two weeks of studies with another new European subject, ME20, who also uses both electric and acoustic stimulation, December 2 - 13. This subject received partial insertion of a Med-El device on one side and has low frequency residual hearing bilaterally.

- Visits during the studies with ME20 by colleague Marcel Pok from Frankfurt a. M., Germany.
- Presentation by Blake Wilson at the 3rd Conference on Bilateral Cochlear Implantation and Bilateral Signal Processing, Würzburg, Germany, December 12-17.

In addition to continuation of our studies both of bilaterally implanted subjects and of subjects with combined electric and acoustic hearing, this quarter also saw the initial implementation and testing of a new type of processing strategy. A previously developed capability for non-real-time preparation of output stimuli files (for input speech token recordings mixed with speech spectrum noise at various signal-to-noise ratios) was employed in modeling speech processors that incorporate dual-resonance nonlinear (DRNL) filters instead of the bandpass filters currently used in CIS processors. Percutaneous subjects SR9 and SR3 participated in the initial evaluation of the use of such filters, which included comparisons among a standard CIS processor and otherwise similar processors using constant DRNL and channel-specific compression. The results of those studies and others based on those initial results will be described in a future report.

In this report we describe new findings regarding combined electric and acoustic stimulation (EAS). Data obtained this quarter with new subjects ME19 and ME20 and EAS data newly obtained with long-time subject SR3 are presented and compared with data from earlier studies with subjects ME6 and ME14 (reported in QPRs 8, 11, and 13 for Project N01-DC-8-2105).

II. Additional Perspectives on Speech Reception with Combined Electric and Acoustic Stimulation

Background

Our investigation of this topic began in August 2000, with initial studies of a subject (ME6) for whom an intentionally shallow electrode insertion had preserved significant low frequency residual acoustic hearing in her implanted ear. In the presence of speech-spectrum noise, her speech reception scores were significantly higher when ipsilateral acoustic stimulation was added to electrical stimulation from her cochlear implant. The combined mode also was associated with better performance whenever any significant difference between combined and electric-only conditions was noted in quiet. Data in quiet and at signal-to-noise ratios of +10 and +5 dB were consistent with the combined mode being less sensitive than electric stimulation alone to the negative impact of increasing levels of noise on speech reception performance. (For more detail, see QPR8 for Project N01-DC-8-2105. Psychophysical studies combining electrical and acoustic stimulation with the same subject were reported in QPR11 for Project N01-DC-8-2105.)

In December 2001 we were able to study a second subject (ME14) with a similar pattern of residual acoustic hearing, but in this case contralateral to her cochlear implant. That subject showed even greater speech reception benefits from combined electric and contralateral acoustic stimulation in the presence of competing speech-spectrum noise than had been seen with ME6. The pattern of the combined mode being less sensitive than electric stimulation alone to the negative impact of increasing levels of noise on performance was clearly confirmed. (For more detail, see QPR13 for Project N01-DC-8-2105.)

Subjects

Recently, we have conducted EAS studies with three additional subjects, each of whom significantly extends our perspective on EAS. Two of the new subjects were referred to us as having residual acoustic hearing both ipsilaterally and contralaterally with respect to their shallow insertion cochlear implants (ME19 and ME20). These subjects provided us with an opportunity to conduct within-subject comparisons of the benefits of ipsilateral and contralateral EAS. Data with one of those subjects generally confirmed but also significantly refined the pattern seen in our previous studies, while results with the other subject represented a clear exception to that pattern. The third addition (SR3) is a long time research subject, much studied in our laboratory, with substantially less residual hearing than our other EAS subjects, but enough to prompt inclusion in these studies in the hope of obtaining similar performance improvements for her in the presence of noise. Unlike the other subjects in this group, SR3 has no chronic experience with EAS stimulation.

Subject ME19 was born in 1942 and experienced a sudden hearing loss during her first pregnancy in 1966. Progressive loss eventually forced her to retire from teaching in 1993 and continued until she became a candidate for a cochlear implant. She reports no family history of hearing loss. Her right ear was implanted in July 2001 by Dr. Wolf-Dieter Baumgartner of the University of Vienna, Austria. In order to maximize the number of useable electrodes while limiting the depth of insertion to preserve residual hearing, a "short" Med-El array was used -- one designed to substitute for a standard length array when obstruction of scala tympani would prevent full insertion. ME19's clinical cochlear implant fitting utilizes nine of the twelve electrodes in the array. She also routinely uses bilateral hearing aids -- Siemens Signia CT devices. She experienced an onset of both tinnitus and vertigo with her hearing loss in 1966. While the tinnitus remains unchanged, she has not experienced vertigo since her cochlear implant surgery. She reports that she routinely uses both hearing aids together with the cochlear implant. She reports that she can make some use of the telephone, and that her residual hearing is better in the left ear than the right. Her speech reception performance was minimal immediately after surgery and has improved gradually over the period since implantation, but remains less than has been seen in the other EAS subjects we have studied. She still finds lip reading helpful in most circumstances.

There is neither a family history nor any other indication of a cause for the hearing loss that led to subject ME20's receiving a cochlear implant. Born in 1953, she first noticed a change in her hearing during high school. At age 26 she was fitted with a hearing aid on the right side, and added a second aid on the left at age 30. She was implanted on the right side in September 2001 by Dr. Jan Kiefer of the University of Frankfurt, Germany. A standard Med-El electrode array was inserted 22 mm into scala tympani. SR20 experienced tinnitus bilaterally before cochlear implantation but only on the left side since then, and to a degree that she does not find bothersome. She denies any history of vertigo before or after implantation. She experienced good speech reception immediately upon first fitting of her clinical processor, and her overall performance is now excellent. She does report difficulty, however, using a telephone with either the left ear (residual hearing alone) or the right (residual hearing and implant), and switches to a different program whenever using her processor to carry on a telephone conversation.

Subject SR3 was born in 1937. She first noticed and documented a hearing loss in 1957, while training to become a nurse. Over the next 15 years, fluctuations in her hearing -- rapid drops followed by spontaneous recovery after one to two weeks -- were superimposed on a slow deterioration. Attempts to correlate such episodes with a variety of things (diet changes, exposure to allergens, tension, barometric pressure, etc.) were unsuccessful. An extensive series of diagnostic procedures in 1973 failed to reveal any abnormality, after which vasodilation therapy seemed to slow the progressive loss until 1983 when it began to increase rapidly. Another extensive series of tests revealed only an abnormality in thyroid function that was quickly corrected by a change in chronic medications. The hearing lost during that period was never recovered. A left ear shunt was performed in 1984 for Mondini syndrome. Dr. Bruce Gantz of the University of Iowa implanted an Ineraid percutaneous electrode array on SR3's left side late in 1987. She was first seen in our laboratory in March 1990, when she volunteered to be a research subject in our first comparisons of CIS processors to the compressed analog strategy of the clinical Ineraid devices. Her performance was substantially improved by use of a CIS strategy, and she subsequently began to use a Med-El CIS-Link device as her clinical processor. She has returned to our laboratory on numerous occasions to take part in a variety of studies benefitting from percutaneous access to implanted electrodes. We knew that some residual hearing on the right side had led one physician to discourage SR3 from having cochlear implant surgery in 1987, but in our laboratory studies we found that she didn't even notice normal conversation taking place in the testing room when her cochlear implant was turned off or was receiving signals via direct connection to a prerecorded source. In the light of the striking benefits seen recently for combined electric and acoustic stimulation in the presence of speech spectrum noise, we decided to assess SR3's contralateral residual hearing and its potential as an adjunct to her cochlear implant system. She has not used a hearing aid since receiving her cochlear implant.

We note that the previously-studied subject ME6 also had and has some residual hearing in the ear contralateral to the implant. As indicated in Figures 1 and 2 below, that hearing was not as good as the hearing on the ipsilateral side. Our work to date with her has been limited to tests involving the implanted ear only.

Studies

Most of our subjects were able to provide us with copies of clinical audiograms obtained post-implantation, typically at the time of first fitting of a cochlear implant speech processor. The clinical audiograms we have available are summarized in Figure 1, where each subject has been assigned a unique symbol shape and line color, and symbols corresponding to ears that are ipsilateral and contralateral to the site of electric stimulation are shown as open and filled, respectively. Included are a total of six ears, across four of our five subjects. (Audiograms for each of the fifth subject's ears have been requested from the referring clinic.)

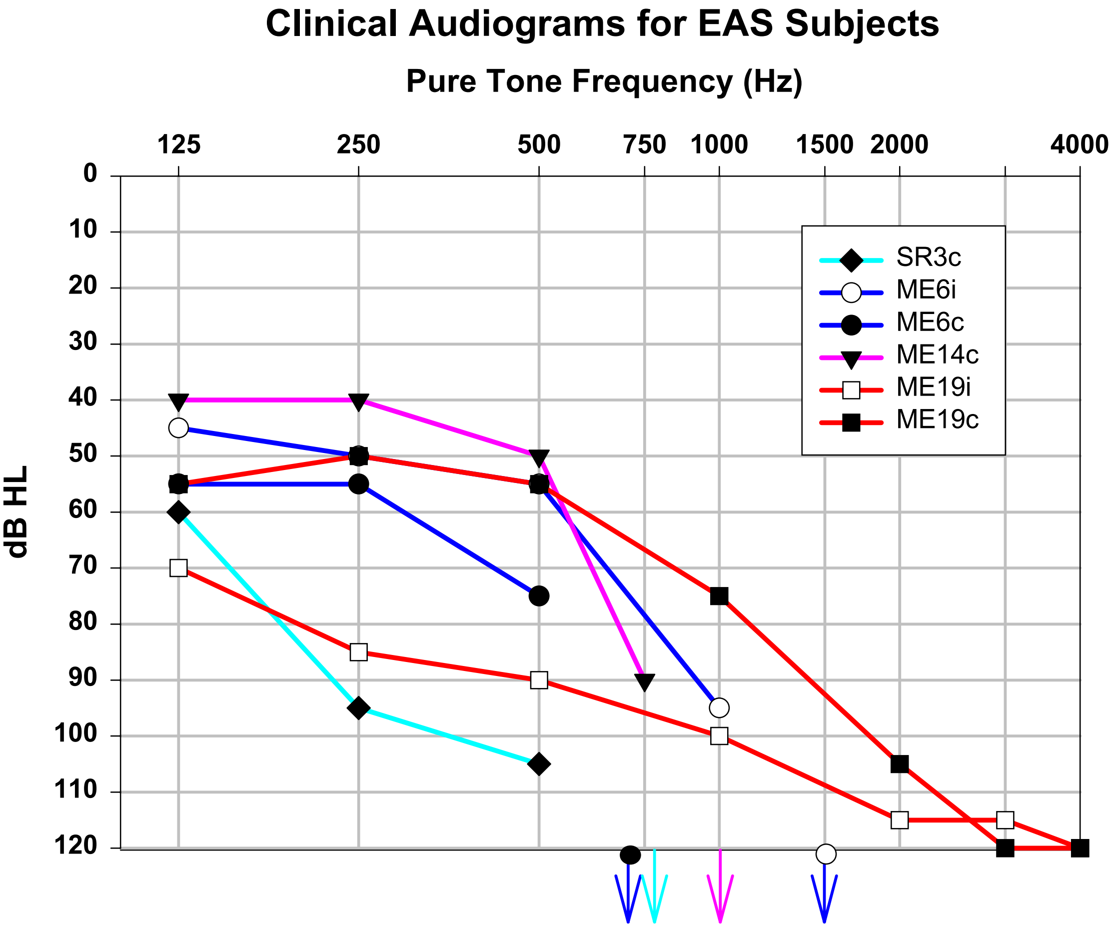

Figure 1. Clinical Audiograms. Relative Pure Tone Thresholds *vs.* Frequency at standard audiometric frequencies for each ear with significant residual hearing. Symbol shapes and line colors are associated with individual subjects. Open and filled symbols indicate residual hearing that is ipsilateral and contralateral, respectively, to the cochlear implant. Six ears are represented, across four of the five subjects.

The overall pattern was one of various degrees of survival of residual hearing for pure tone frequencies below 1 kHz. An audiogram, of course, provides only a partial indication of the nature of any residual hearing. Also important are the degree of frequency discrimination across the residual spectrum, and the nature of loudness growth and recruitment.

To better characterize and compare the individual degrees and patterns of residual hearing, we obtained our own high resolution audiograms for each of the subjects at the time of their visits to our laboratories. These document relative thresholds for pure tones at 100 Hz intervals from 100 Hz to the upper limit of each subject's residual hearing. These data are displayed in Figure 2, for all eight ears with significant residual hearing across our five subjects. The symbols and color coding are consistent across Figures 1 and 2.

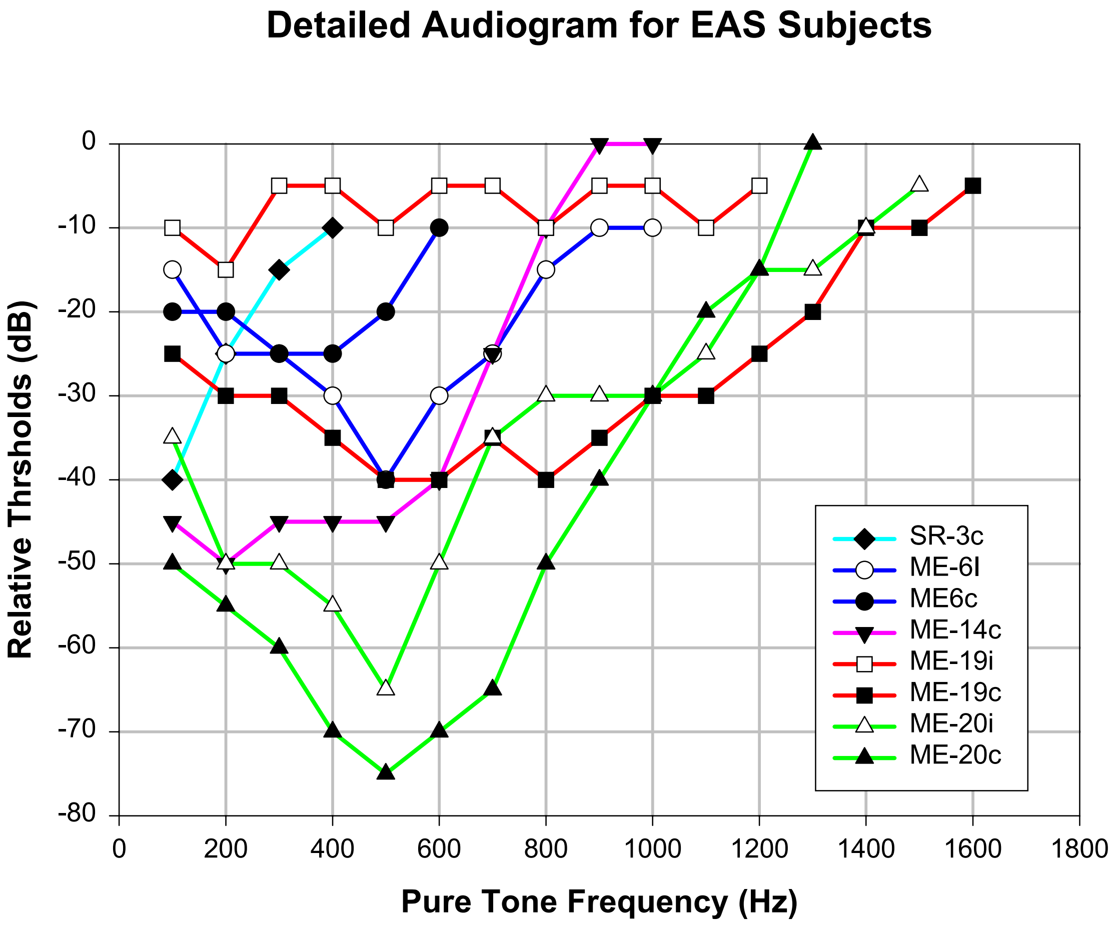

Figure 2. Detailed Audiograms. Relative Pure Tone Thresholds *vs.* Frequency at 100 Hz intervals for each ear with significant residual hearing. Obtained under earphones. Symbol shapes and line colors are associated with individual subjects, and are consistent with those used in Figure 1 above. Open and filled symbols indicate residual hearing that is ipsilateral and contralateral , respectively, to the cochlear implant. Eight ears are represented, across the five subjects. Note that better hearing corresponds to points nearer the bottom in Figure 2, but nearer the top in Figure 1.

As may be seen in Figure 2, a wide range of degrees and spectral extents of residual hearing are represented among these eight ears. The thresholds span a 40 dB range at 100 Hz, and approach a 70 dB range at 500 Hz. The upper frequency limit of residual hearing varies from 1300 Hz to less than 250 Hz for a -20 dB threshold criterion for each subject's better ear, and from 1100 Hz to less than 200 Hz for a -30 dB criterion. Comparisons between the two figures indicate that a relative threshold of -20 dB in Figure 2 corresponds roughly to a hearing loss of 80 dB in Figure 1, and a -30 dB relative threshold to about 70 dB HL. Our initial two EAS subjects, ME6 and ME14, have very similar audiograms at and above 500 Hz, while below that frequency ME14 has substantially better hearing than ME6's better-hearing ear (ipsilateral to the implant). Between our two most recent subjects, one (ME19) has much more residual hearing contralaterally than ipsilaterally, while the other (ME20) has quite similar patterns of surviving hearing on both sides. The residual hearing of our long-term subject SR3 is limited to a narrower frequency range than any of the chronic EAS users. In some of the figures to follow, labeling will be used to distinguish between generally "good" and "poor" levels of residual hearing. In such cases, only the (contralateral) residual hearing of SR3 and the ipsilateral residual hearing of ME19 will be characterized as relatively poor.

Both consonant and sentence materials were used to compare speech reception with various combinations of electric and acoustic stimulation in these five subjects. Identification of medial consonants in an /a/-C-/a/ context was one measure used with all five subjects. The consonant tests used multiple exemplars and provided no feedback as to correct or incorrect responses, with the tokens randomized in sets to allow statistical analysis of uncertainty. Two of the subjects (ME14 and SR3) were tested with the corpus of 24 English consonants routinely used in our laboratory when overall performance levels are high. The other three subjects (ME6, ME19, and ME20), whose native language is German, were tested with a subset of 16 of the same consonants, selected and relabeled as appropriate to that language. ME6's command of English was good enough to allow use of the CUNY sentence materials with her as well as with native English speakers ME14 and SR3. For Austrian and German subjects ME19 and ME20, the sentence test materials chosen were from the Oldenburger Satztest. Each of those sentences is composed of one word from each of five closed sets, in the order: name, verb, number, adjective, and noun. Each of the five closed sets contains ten words [see Wegener, Kuhnel, and Kollmeier, *Z. Audiol* **38** (1), 4-15 (design); (2), 44-56 (optimization); and (3), 86-95 (evaluation)] . While not an open set test as in the CUNY corpus, these materials are not contaminated by even extensive previous use, and do constitute natural connected speech. A minimum of four lists of the CUNY sentences were used for each condition (approximately 408 words) and a minimum of four lists of the Oldenburger sentences (200 words). In the case of both types of sentence test, the scores recorded were percent correct word identification.

In all cases involving competing noise, CCITT long term speech spectrum noise was added to the speech signals to produce a specified signal-to-noise ratio (S/N). In these studies, all noise and speech signals were HRTF processed for incidence from the same direction (front), without the inclusion of any ear canal effects.

Results

We begin with a comparison of results among the three subjects using residual hearing in only one ear. This includes original subjects ME6 and ME14 and our long-term subject with relatively poor residual hearing contralateral to her cochlear implant (SR3). Figure 3 summarizes speech reception results for identification of consonants and identification of words in CUNY sentences as a function of S/N ratio, and does so for electric stimulation only, for combined electric and acoustic stimulation, and for acoustic stimulation only. The cochlear implant speech processors analyzed a full 350 - 5500 Hz overall frequency range in each of these cases.

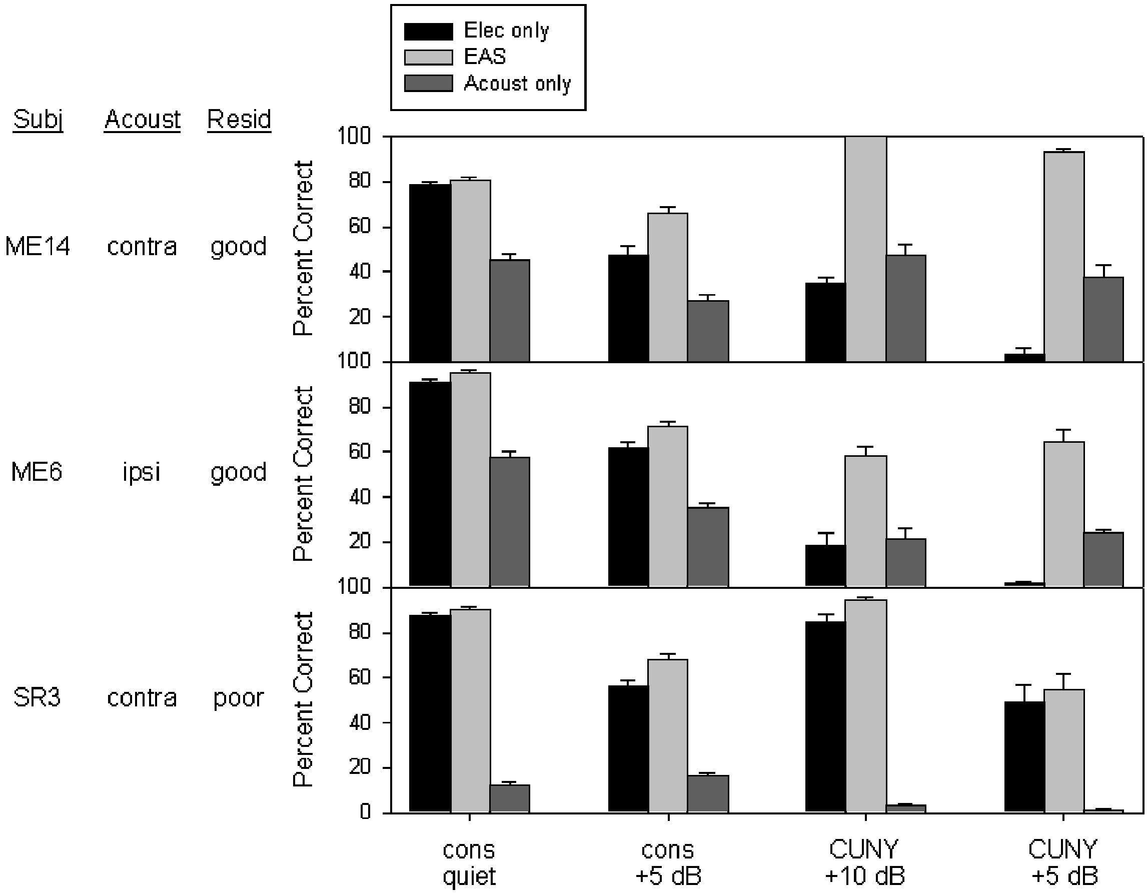

Figure 3. Speech Reception Results for subjects using residual hearing in one ear only. Percent correct scores for identification of 24 medial English consonants (ME14 and SR3) and 16 medial German consonants (ME6) in quiet and at +5 dB with respect to CCITT speech spectrum noise, and for identification of words in English-language CUNY sentences at +10 dB and +5 dB with respect to the same noise. Labels to the left indicate whether residual acoustic hearing is ipsilateral or contralateral to the electrically stimulated ear, and the degree of that residual hearing for each of three subjects. Each group of three bars indicates scores, from left to right, for electric stimulation only, combined electric and acoustic stimulation, and acoustic stimulation only. Error bars indicate standard deviation of the mean. The overall cochlear implant speech processor analysis frequency range was 350 - 5500 Hz in every case. Data for these and a few additional conditions are included in tabular form in Appendix 2.

In four of the cases shown in Figure 3, for consonants in quiet and CUNY sentences at a S/N of +10 dB, percent correct scores for combined electric and acoustic stimulation are high enough to raise the possibility of differences being distorted because of ceiling effects. The corresponding electric only results for consonants in quiet are subject to the same possibility.

The data for ME14 and ME6 shown in Figure 3 have been discussed previously and were summarized in the background section of this report. Of particular interest, then, is whether subject SR3, our long-term cochlear implant subject with substantially less residual hearing than either ME6 or ME14 and no chronic experience with EAS, can achieve significantly better speech reception in noise with combined stimulation. While her acoustic-only scores are, as expected, much lower for all combinations of test and S/N shown, the combined EAS mode does support significantly better scores than electric-only for consonants at the S/N of +5 dB. For CUNY sentences at a S/N of +10 dB, while the corresponding scores differ from each other by more than a standard deviation of the mean, the significance of the difference is not clear (p = .054). Electric-only and EAS results for the CUNY sentences clearly are not significantly different when the S/N is only +5 dB, and combined EAS performance for SR3 does not seem to be any less sensitive to the impact of increased noise than her performance with the cochlear implant alone.

A similar summary is presented in Figure 4 (shown on the next page) for our two new subjects, each of whom has residual hearing both ipsilaterally and contralaterally with respect to her cochlear implant. Shown in the figure are speech reception results for identification of consonants and identification of words in Oldenburger sentences as a function of S/N, comparing scores for electric stimulation only, combined electric and acoustic stimulation, and acoustic stimulation only. Results are shown for each subject with acoustic stimulation ipsilateral to the electrical stimulation, contralateral to it, and both. (The same electric-only data are reproduced across all three acoustic condition panels for each subject.) As in the previous figure, the cochlear implant speech processors represented here analyzed a full 350 - 5500 Hz overall frequency range. Conditions without bars in the figure were not tested because of time limitations.

As was the case in Figure 3, Figure 4 includes several comparisons that may be distorted by including scores high enough to be subject to ceiling effects. This is the case for the six highest combined EAS scores for subject ME20, for consonants in quiet and Oldenburger sentences both in quiet and at a S/N of +5 dB. It also is the case for both electric-only and acoustic-only scores for ME20's identification of words in Oldenburger sentences in quiet.

With her relatively poor ipsilateral residual hearing, ME19's scores show no advantage for combined EAS stimulation except for the single case of Oldenburger sentences in quiet. In noise, her residual hearing -- whether ipsilateral, contralateral, or both -- seems in general to account fully for her EAS scores. This pattern is strikingly different from that of our other subjects, especially considering that our detailed audiograms indicate that ME19's contralateral residual hearing is equal to or more sensitive than ME6's ipsilateral residual hearing at all frequencies.

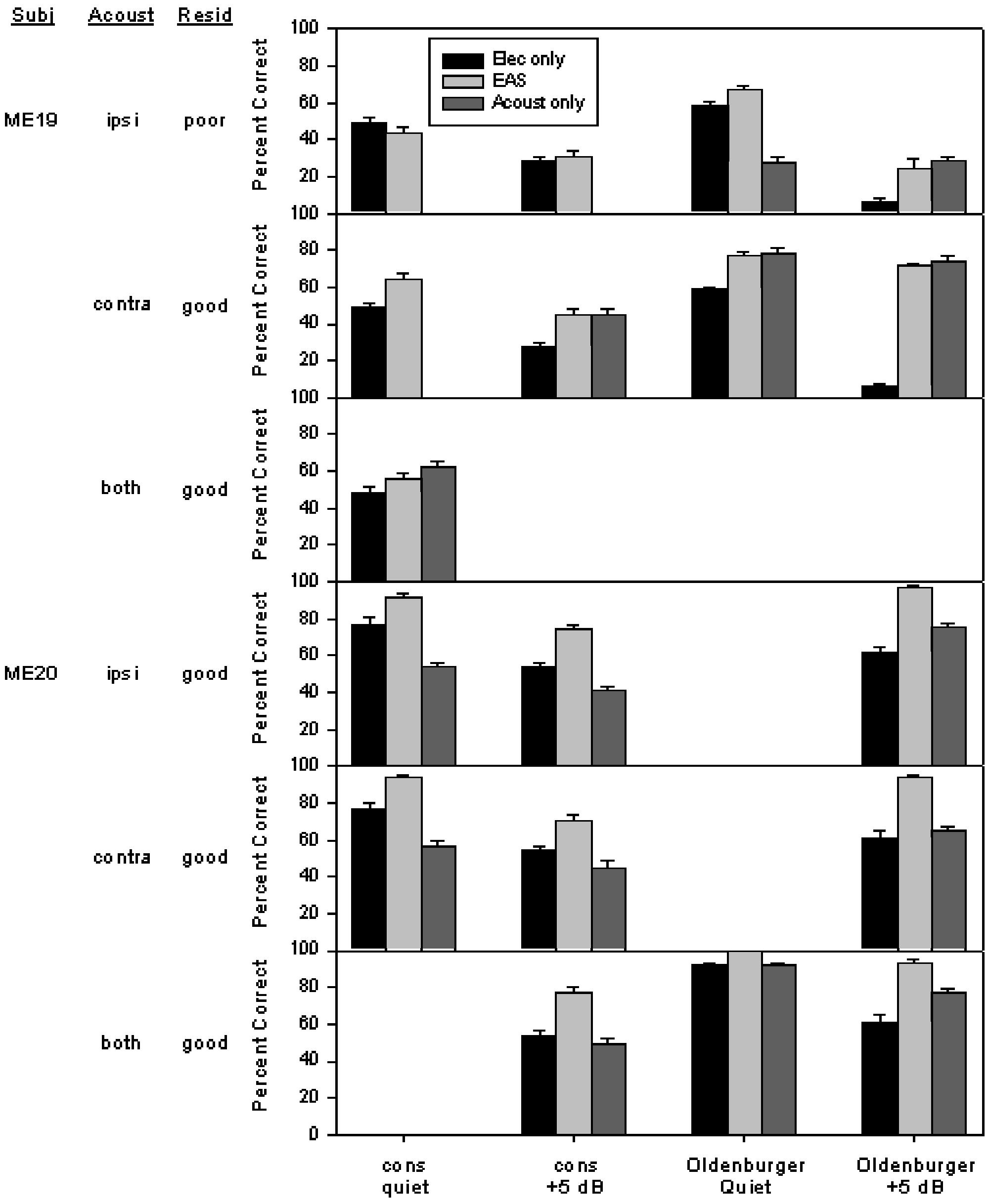

Figure 4. Speech Reception Results for subjects tested with acoustic stimulation of either ear or both ears. Percent correct scores for identification of 16 medial German consonants in quiet and at the S/N of +5 dB with respect to CCITT speech spectrum noise, and for identification of words in German Oldenburger formulaic sentences in quiet and at +5 dB with respect to the same noise. Labels to the left indicate results corresponding to the use of residual acoustic hearing that is ipsilateral to the electrically stimulated ear, contralateral to that ear, or to both ears, and the degree of the residual hearing in each case. Each group of three bars indicates scores, from left to right, for electric stimulation only, combined electric and acoustic stimulation, and acoustic stimulation only. Error bars indicate standard deviation of the mean. The overall cochlear implant speech processor analysis frequency range was 350 - 5500 Hz in every case. Data for these and a few additional conditions are included in tabular form in Appendix 2. Conditions shown here without bars were not tested.

ME20's results -- both with ipsilateral and contralateral acoustic contributions -- are more consistent with those of our earlier subjects. Also, as might be expected on the basis of the similarity of her left and right audiograms, her ipsilateral and contralateral results are quite similar to each other. These results are consistent with earlier patterns in the superiority of electric-only over acoustic-only performance for consonants in quiet, and the superiority of EAS over either mode alone, especially for sentences in noise. Apparently inconsistent with patterns based on the earlier studies is performance with EAS not being markedly less sensitive than electric stimulation alone to the negative impact of noise increasing from quiet to a S/N of +5 dB. As may be seen in Appendix 2, however, ME20's performance does show the same pattern, but only at somewhat higher levels of noise, e.g. going from +5 dB S/N to 0 dB.

To facilitate comparisons of any advantage offered by combined EAS, in Figure 5. (a-c) we replot the data of Figures 3 and 4 as differences between percent correct scores with EAS and the higher of the electric-only and acoustic-only scores under the same test conditions. This constitutes a measure of EAS benefit with respect to the next best alternative.

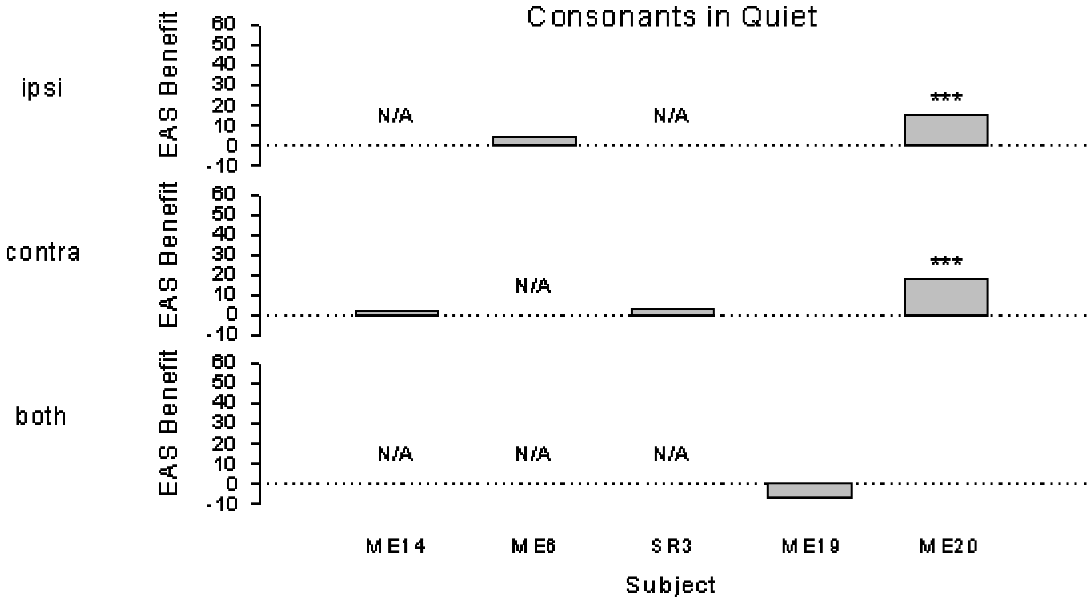

Figure 5. (*continued on next page*)

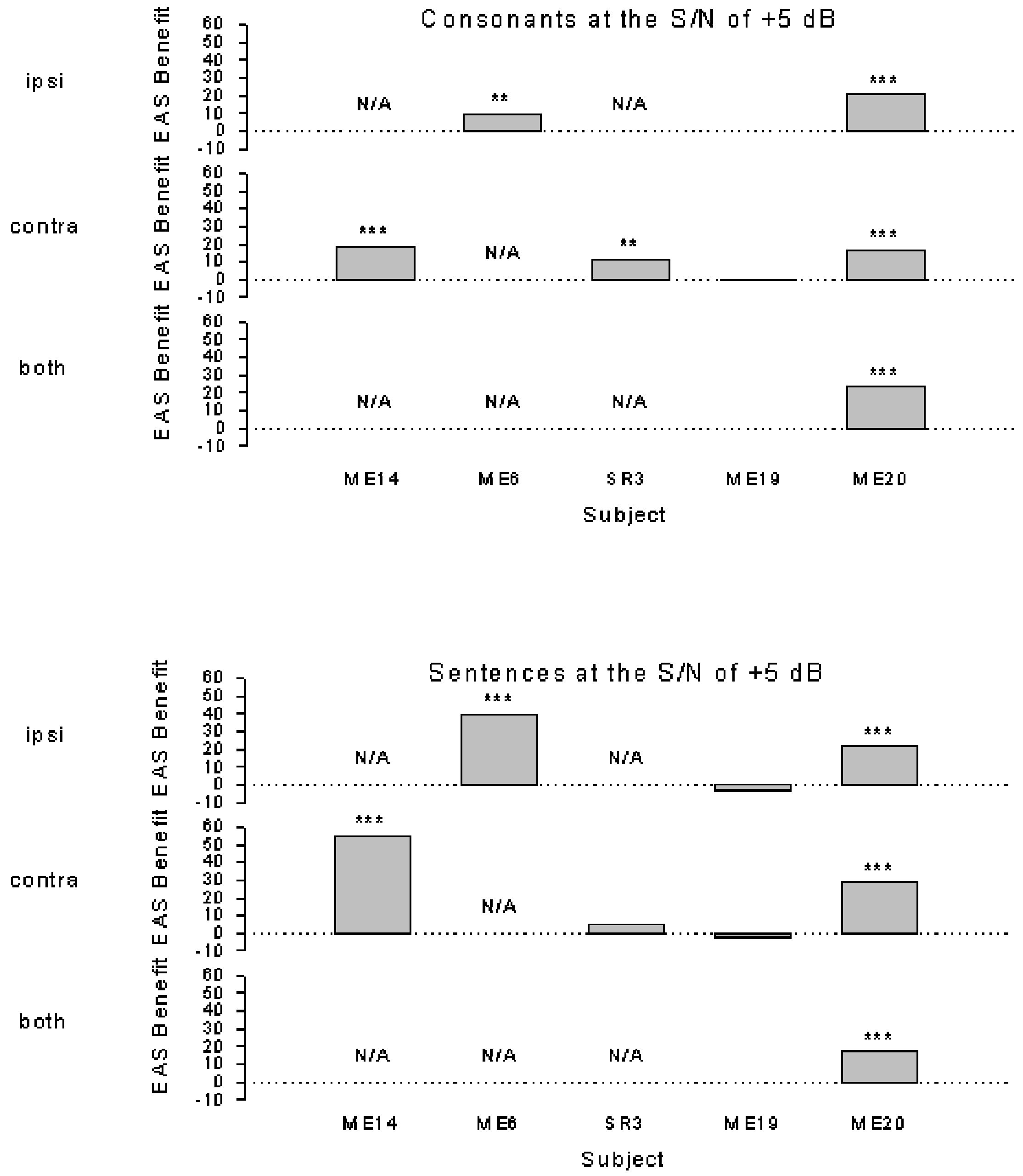

Figure 5. EAS Benefit with respect to the next best alternative. The difference between the speech reception score attained with EAS and that obtained with the better of the electric-only and acoustic-only scores for each indicated condition (from data of Figures 3 and 4 above). Conditions marked "N/A" are those for which residual hearing was not available on the appropriate side. Double and triple asterisks mark differences that are significant at $p <= 0.01$ and $p <= 0.001$, respectively; all other differences are not significant. The overall cochlear implant speech processor analysis frequency range was 350 - 5500 Hz in every case.

The most obvious trend in these difference data is the general increase in EAS benefit with increasing noise (consonants in quiet at the top of the figure *vs.* consonants at a S/N of +5 dB in the middle) and, in noise, the greater EAS benefit for identification of words in sentences than for identification of isolated consonants (consonants at +5 dB S/N in the middle of the figure *vs.* sentences at +5 dB S/N at the bottom). In the cases of the sentence data for subjects ME6 and ME14, the EAS benefit reflects EAS scores greater even than the sum of the electric-only and acoustic-only scores.

A second pattern is the absence of any obvious advantage to either ipsilateral or contralateral electric stimulation *per se* (compare "ipsi" and"contra" rows within each of the three sections of the figure). The results for subjects ME19 and ME20 to our studies contribute especially to this finding by offering direct within-subject comparisons of ipsilateral and contralateral acoustical contributions.

Finally, no negative difference in the figure is statistically significant, so we have found no evidence of any destructive interaction between the two modes of stimulation.

All the data shown thus far have been for cochlear implant processors that analyzed an overall pass band of 350 - 5500 Hz, a range shared by many processors studied in our laboratory. Our previous EAS studies also included comparisons with processors restricted to overall analysis ranges of 600 - 5500 Hz and 1000 - 5500 Hz, designed to explore possible effects of overlap between the spectral ranges represented electrically and acoustically, or of a gap between those spectral ranges. Figure 6 compares speech reception data for electric stimulation only, using each of those electrical analysis ranges, for each of our five subjects.

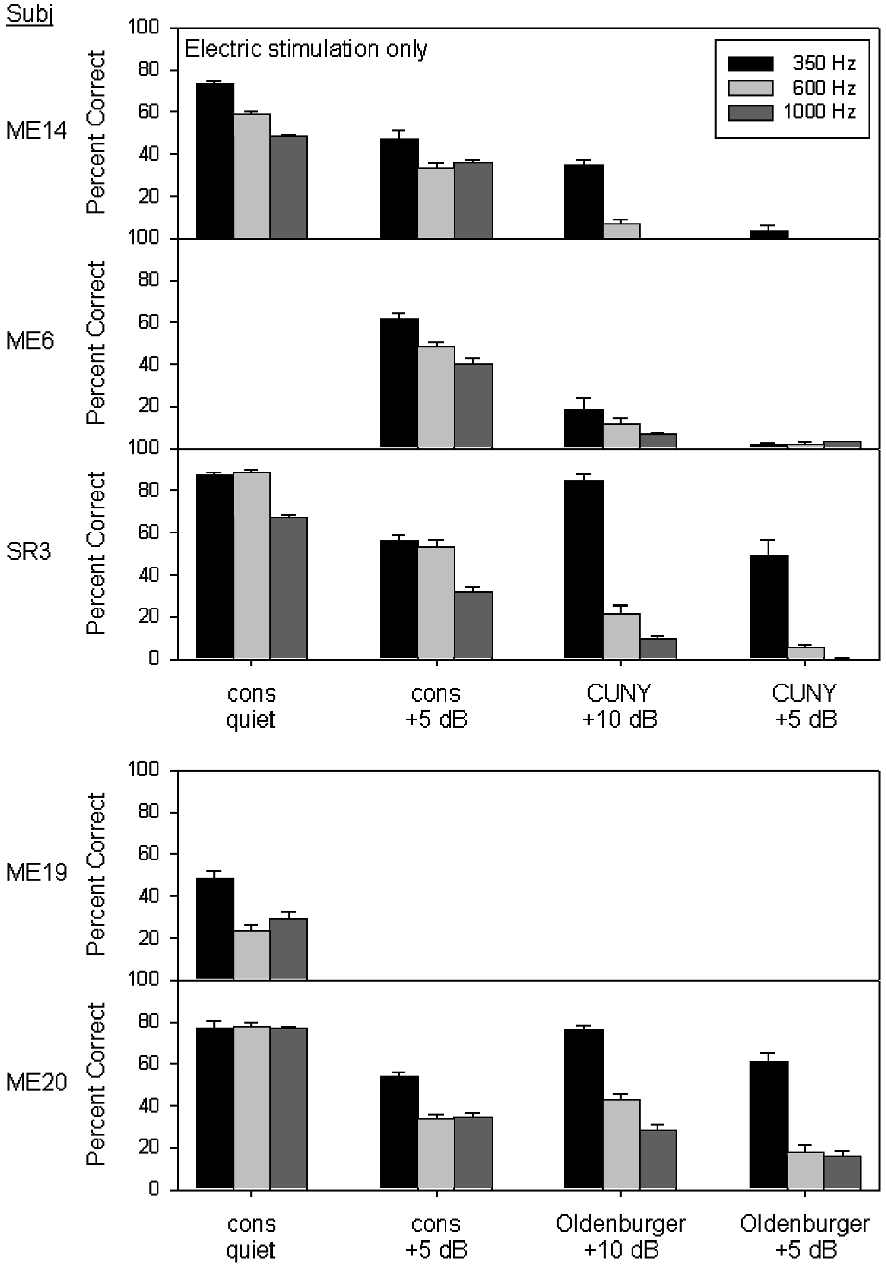

Figure 6. Effects of Changes in Minimum Frequency of Overall Implant Pass Band: Electric Stimulation Only. Percent correct speech reception scores. The three subjects in the upper group of panels were tested with English sentence materials (CUNY), and the two in the lower group of panels were tested with German sentence materials (Oldenburger). Each group of three bars indicates scores, from left to right, for overall analysis pass bands extending from 5500 Hz down to 350 Hz, 600 Hz, and 1000 Hz, respectively. Data were collected for all tests and minimum frequencies for subject ME14, and included zero scores for the combinations for which no bar is visible. Consonant tests in quiet were not conducted with subject ME6 for the minimum frequencies of 600 and 1000 Hz. Similarly, those frequencies were not included for any but the consonant tests in quiet for subject ME19. Error bars indicate standard deviation of the mean. Data for these and a few additional conditions are included in tabular form in Appendix 2.

As would be expected for electric stimulation alone, a performance advantage for the widest overall analysis band (350 - 5500 Hz) was seen for every subject.

Figure 7 shows similar comparisons for combined electric and acoustic stimulation

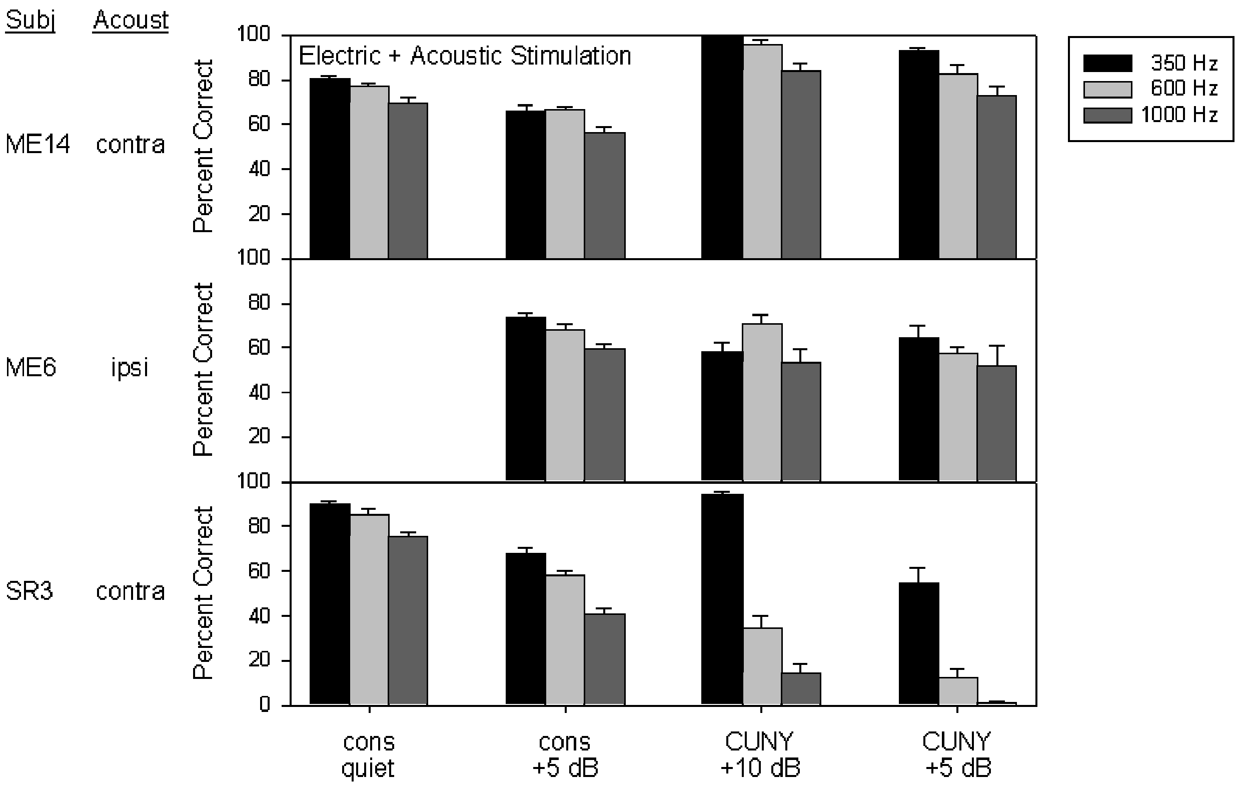

Figure 7. ***(continued on next page)***

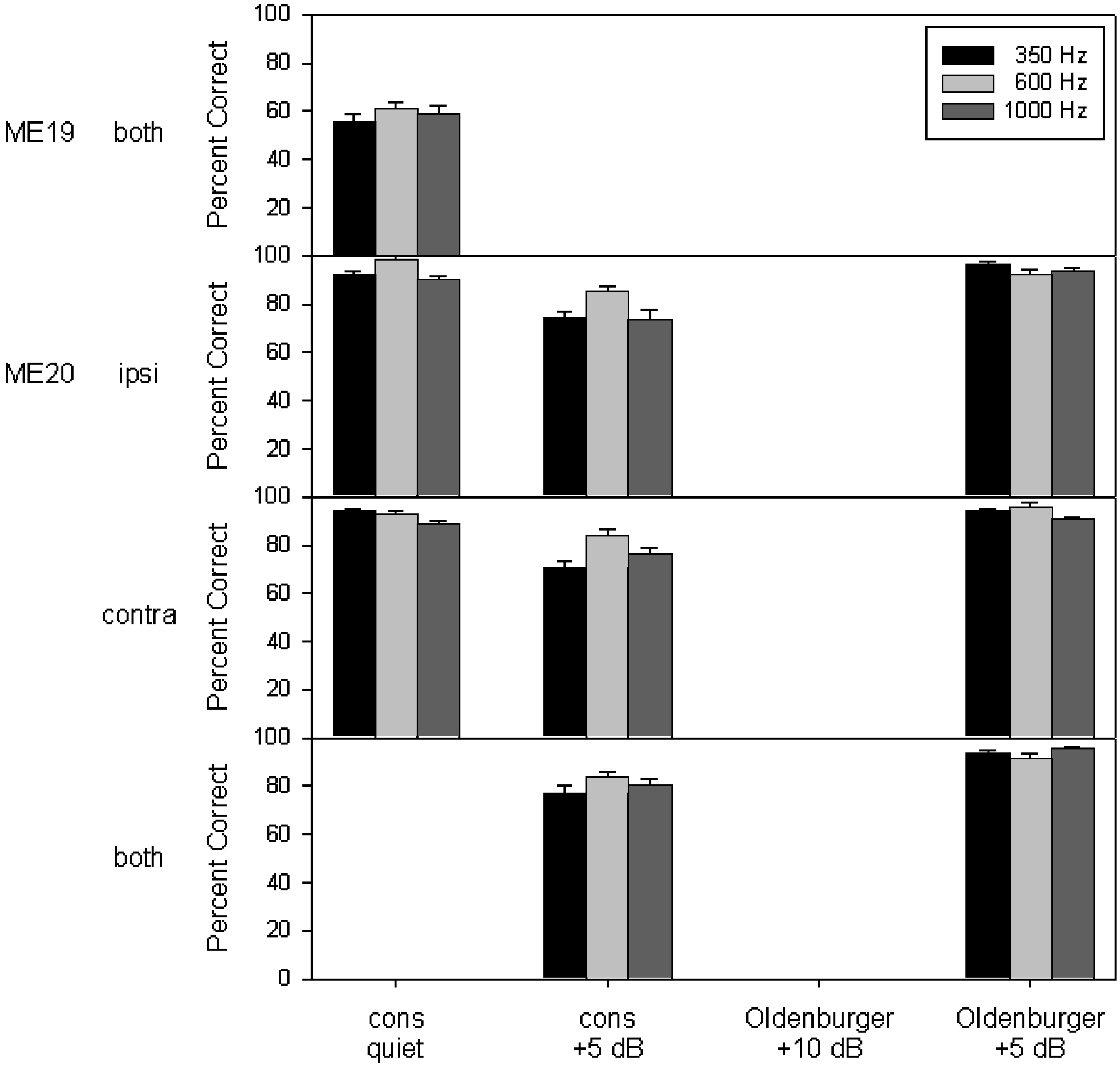

Figure 7. Effects of Changes in Minimum Frequency of Overall Implant Pass Band: Combined Electric and Acoustic Stimulation. Percent correct speech reception scores. Entries in the "Acoust" column indicate whether the acoustic stimuli were delivered ipsilaterally or contralaterally with respect to the electrical stimuli, or to both ears. The three subjects in the upper group of panels were tested with English sentence materials (CUNY), and the two in the lower group of panels were tested with German sentence materials (Oldenburger). Each group of three bars indicates scores, from left to right, for overall analysis pass bands extending from 5500 Hz down to 350 Hz, 600 Hz, and 1000 Hz, respectively. Bars are shown only for those combinations of tests and subjects for which all three minimum frequencies were included. Error bars indicate standard deviation of the mean. Data for these and a few additional conditions are included in tabular form in Appendix 2.

There are several instances in which percent correct scores in Figure 7 are high enough that ceiling effects may distort differences among them. This is the case, for instance, for ME14's sentence data at a S/N of +10 dB, and for ME20's consonant data in quiet and sentence data at +5 dB.

For ME14 and SR3 there are clear advantages to the use of the widest overall analysis range, 350 - 5500 Hz.

While there are significant performance differences among the three ranges for ME6's consonant data at S/N = +5 dB and for her CUNY sentence data at S/N = +10 dB, there is no overall pattern of advantage across those conditions.

The limited data for ME19 show no significant differences.

For ME20, there are significant advantages for the 600 - 5500 Hz overall frequency range wherever the scores are not clearly subject to ceiling effects (consonants at a S/N of +5 dB). This is true for both ipsilateral and contralateral acoustic stimulation in this subject who has nearly equivalent patterns of residual hearing on both sides. This advantage for the 600 - 5500 Hz range means even larger EAS benefit values than those shown in Figure 5 for ME20 using the 350 - 5500 Hz range.

Summary

- For some subjects, speech reception scores in noise for combined EAS stimulation exceed the sum of their scores with electric stimulation alone and acoustic stimulation alone.
- Even an extremely limited range of residual hearing can support some improvement in speech reception in the presence of speech spectrum noise. SR3’s residual pure tone threshold rises by 30 dB between 100 Hz and 400 Hz (see Figure 2). Yet, the addition of acoustic stimulation to the use of her contralateral cochlear implant produces significant improvements in her scores for identification of consonants at a S/N of +5 dB. While her improvement with EAS is not significant for sentences at +10 and +5 dB, her results indicate potential for meaningful improvements in performance in the face of competing noise for cochlear implant users with substantially less residual hearing than some of our subjects.
- Comparable ranges and degrees of residual hearing, however, do not assure comparable benefits from combined EAS stimulation. Subject ME19’s detailed audiogram indicates levels of residual hearing superior to those of subject ME6 at all frequencies; yet her scores in tests of consonant and word identification in speech spectrum noise show no EAS benefit.
- There is no indication of any difference in the EAS benefits to speech reception in speech spectrum noise depending on whether ipsilateral or contralateral residual hearing is used in conjunction with electrical stimulation. This now has been shown in within-subject comparisons as well as across subjects.
- Our subjects typically show a decreased sensitivity to the negative effects of additional noise with combined electric and acoustic stimulation as compared with electric

stimulation alone. Some subjects require higher levels of noise than others to demonstrate such an effect (subject ME20, in comparison with subjects ME6 and ME14).

- In some cases, speech reception performance is improved by raising the low frequency boundary of the overall band analyzed by the cochlear implant speech processor, reducing overlap with the range of frequencies conveyed via acoustic stimulation.

III. Plans for the next quarter

Among the activities planned for the next quarter are:

- Continuing studies with local subject ME16, implanted bilaterally with Med-El Tempo+ devices.
- Visits by Luc Van Immerseel and Filiep Vanpoucke of the University of Antwerp, January 23 - February 3.
- Two weeks of studies with a new European subject, ME21, January 27 - February 6.
- A visit by Christoph Arnoldner from the University of Vienna in association with the studies of ME21, January 27 - February 7.
- A visit by Charlie Miller of the University of Iowa, March 17 - 18.
- A visit by Kevin Franck of the Center for Childhood Communication, The Children's Hospital of Philadelphia, March 19 - 20.
- An invited keynote presentation by Dewey Lawson to the annual spring meeting of the North Carolina Chapter of the American Association of Physics Teachers, March 21.
- An invited presentation by Blake Wilson to the 6th Meeting of the German Audiological Society (Deutsche Gesellschaft für Audiologie) in Würzburg, Germany, March 26 - 29.

IV. Acknowledgments

We thank volunteer research subjects SR3, SR9, ME6, ME14, ME16, ME18, ME19, and ME20, who participated in studies conducted during this quarter and/or whose participation made possible results presented in this report.

Appendix 1. Summary of reporting activity for this quarter

Reporting activity for this quarter, covering the period of October 1 through December 31, 2002, included:

Invited Talks

Wilson BS: The RTI's perspective on bilateral cochlear implantation. *Wullstein Symposium 2002*, Würzburg, Germany, December 12-17, 2002. (This second *Wullstein Symposium* included the *3rd Conference on Bilateral Cochlear Implantation and Bilateral Signal Processing*, the *7th International Cochlear Implant Workshop*, and the *1st Workshop on Binaural Rehabilitation.*)

Wilson BS: Speech processors for auditory prostheses. *33rd Annual Neural Prosthesis Workshop*, National Institutes of Health, Bethesda, MD, October 16-18, 2002.

Wilson BS: Evaluation of combined EAS in studies at the Research Triangle Institute. *Hearing Preservation Workshop*, Indiana University School of Medicine, Indianapolis, IN, November 8-10, 2002.

Lawson DT: Recent Progress and Current Areas of Emphasis in Cochlear Implant Research, *Annual Meeting, North Carolina Chapter of the Acoustical Society of America,* Raleigh, NC, November 8, 2002.

Chaired Conference

Miyamoto RT, Wilson BS (Co-Chairs): *Hearing Preservation Workshop*, Indiana University School of Medicine, Indianapolis, IN, November 8-10, 2002.

Chaired Session

Wilson BS (Session Moderator): Evaluation of combined electric and acoustic stimulation of the auditory system. *Hearing Preservation Workshop*, Indiana University School of Medicine, Indianapolis, IN, November 8-10, 2002.

Honors

Wilson was a Guest of Honor at the *Wullstein Symposium 2002* (*3rd Conference on Bilateral Cochlear Implantation and Bilateral Signal Processing, 7th International Cochlear Implant Workshop*, and *1st Workshop on Binaural Rehabilitation*), Würzburg, Germany, December 12-17, 2002.

Appendix 2. Table of speech reception results

This table contains percent correct scores for medial consonant identification (“M”) and CUNY English and Oldenburger German sentences (“Sent.”). The data were obtained at a variety of S/N values with respect to CCITT long term speech spectrum noise and in quiet (“+0, +5, +10, Qt”). Conditions included acoustic stimulation alone (“Acoust. Alone,”), electric stimulation alone (“Elec. Alone”) , and combined electric and acoustic stimulation (“Elec/Acoust”). Cases including acoustic stimulation involved use of headphones and signals from 1 Khz low-pass filters, and are further labeled to indicate whether left, right, or both ears were involved. Conditions involving use of electrical stimulation are further labeled to indicate the overall frequency range (pass band) analyzed (*e.g.,* “350/5500” indicates the range 350 – 5500 Hz), and the side stimulated. Unless otherwise indicated by a footnote, the pulse width for electric stimuli was 12µs/phase for SR3 and 27µs/phase for all other subjects. Unless otherwise indicated by a footnote, the pulse rate for electric stimuli was 2273 p/s in each channel. Data not summarized in Figures 3, 4 , 6, and 7 are highlighted like this.

Subject SR3

Condition	Freq. Range	Electrs.	M Qt	M +5	Sent. Qt	Sent. +10	Sent. +5	Sent. +0
Elec. Alone L	350/5500	123456	87.1±1.9	56.3±2.7		84.3±3.9	49.2±7.2	
	600/5500		88.8±1.5	53.3±3.3		21±4.6	5.3±1.6	
	1000/5500		67.1±1.6	31.7±2.8	73.2±2.4	9.3±1.8	0.2±0.2	
Elec/Acoust L/R	350/5500		90.4±1.3	67.9±2.8		94.1±1.3	54.4±7.3	
	600/5500		85.4±2.3	57.9±2.6		34.3±6.0	12.5±4.1	
	1000/5500		75.4±2.4	40.4±3.0	74.7±4.7	14.2±4.1	1.2±0.4	
Acoust. Alone R			12.1±1.8	16.3±1.7	3.9±1.0	3.1±0.5	1.2±0.7	

Subject ME19

Condition	Freq. Range	Electrs.	M Qt	M +5	Sent. Qt	Sent. +10	Sent. +5
Elec. Alone R	350/5500	123568,11,12	48.8±2.9	28.2±2.1	59±1.3		6±1.6
	600/5500		23.8±2.4				
	1000/5500		28.8±3.5				
Elec/Acoust R/L+R	350/5500		55.6±3.0				
	600/5500		61.3±2.2				
	1000/5500		58.8±3.5				
Elec/Acoust R/R	350/5500		45.6±4.7	31.3±4.2	67±2.4		24.5±4.5
Elec/Acoust R/L	350/5500		63.8±3.1	44.4±3.4	77.5±2.1		71.5±1.71
*	1000/5500		65±2.5	47.5±2.3	82.5±1.7		76±3.5
	1000/5500	56789,10,11,12	65.6±2.7	51.3±3.7			
** ^	1000/5500	579,11	63.8±5.0	53.1±3.5			
^	1000/5500	579,11	61.9±4.0	53.8±4.2			
	1000/5500	68,10,12	50.6±2.7	44.4±2.4			
	1000/5500	579,11	59.4±3.1	44.4±2.2			
	1000/5500	56789,10,11,12					75±2.6
Acoust. Alone R±L			62.5±2.8				
Acoust. Alone L				45.6±2.6	78±3.6		73.5±3.8
Acoust. Alone R					27±3.7		28±2.9

Subject ME20

Condition	Freq. Range	Electrs.	M Qt	M +5	Sent. Qt	Sent. +10	Sent. +5	Sent. +0
Elec. Alone R	350/5500	12345678	76.9±3.5	53.8±2.5	92±0.8	76.5±1.71	61±3.7	20.5±0.5
	600/5500		77.5±2.5	33.8±2.1		42.5±3.0	17.5±4.0	
	1000/5500		76.9±1.0	34.4±2.1		28±2.94	16±2.2	
Elec/Acoust R/L+R	350/5500			76.9±3.1	99±0.6		93.5±1.5	87.5±3.8
	600/5500			83.8±1.9			91.5±2.1	91.5±2.4
	1000/5500			80.0±3.1			95.5±0.5	87.5±3.3
Elec/Acoust R/R	350/5500		91.9±1.9	74.4±2.5			96.5±1.3	
	600/5500		98.8±0.8	85.6±1.9			92.5±1.7	
	1000/5500		90.0±1.7	73.8±3.6			93.5±1.3	

Subject ME20 cont.

Condition	Freq. Range	Electrs.	M Qt	M +5	Sent. Qt	Sent. +10	Sent. +5	Sent. +0
Elec/Acoust R/L	350/5500		94.4±0.6	70.6±2.8			94±1.2	
	600/5500		93.1±1.1	83.8±2.5			96±1.6	
	1000/5500		88.8±1.3	76.3±2.6			91±0.6	
Acoust. Alone R±L			53.8±1.9	49.4±3.2	91.5±1.3		76.5±2.6	74.5±3.6
Acoust. Alone L			56.3±3.2	45.0±3.5			65±1.7	67.5±2.4
Acoust. Alone R			53.8±2.1	40.6±2.5			75±2.9	70±1.4

Subject ME14

Condition	Freq. Range	Electrs.	M Qt	M +5	Sent. Qt	Sent. +10	Sent. +5	Sent. +0
Elec. Alone R	350/5500	315678,10,11	78.3±1.7	47.1±4.1		34.8±2.48	3.2±3.2	
	600/5500		58.8±1.7	33.3±2.6		6.9±1.96	0±0.3	
	1000/5500		48.3±1.1	36.3±1.3		0±0.3	0±0.3	
Elec/Acoust R/L	350/5500		80.4±1.2	65.8±2.8		100±0.3	92.9±1.4	
	600/5500		77±1.3	66.3±1.6		95.8±1.85	82.6±4.0	
	1000/5500		69.6±2.4	56.3±2.5		83.8±3.81	73±4.1	
Acoust. Alone L			45±3.0	26.7±2.9		47.3±5.0	37.7±5.0	

Subject ME6

Condition	Freq. Range	Electrs.	M Qt	M +5	Sent. Qt	Sent. +10	Sent. +5	Sent. +0
Elec. Alone R	350/5500	12345678	90.6±1.9	61.9±2.5		18.6±5.5	1.7±1.1	
	600/5500			48.1±2.3		11.7±2.9	1.7±1.2	
	1000/5500			40±3.1		6.3±1.2	2.9±0.7	
Elec/Acoust R/R	350/5500		95±1.6	71.3±2.1		58.3±4.0	64.2±5.6	
	600/5500			68.1±2.9		70.5±4.1	57.5±2.4	
	1000/5500			59.4±2.3		53.3±6.0	51.9±8.7	
Acoust. Alone R			57.5±2.4	35.6±1.6		21.3±4.9	24.2±1.5	

* maximum MCL levels, ** pulse rate 1135 p/s, ^ pulse width 54µs/phase