

Third 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 in this quarter included:

- Studies with Clarion subject MI-5 (April 13). The main purpose of these studies was to characterize the current sources in the Clarion implant with recordings of scalp potentials produced with different commanded levels of pulse amplitude. Speech reception with alternative choices of parameter values for CIS processors also was measured.
- Ongoing studies with Ineraid subject SR2, who now is working with us for one or two days each week. Studies in this quarter included continuation of two extensive series of measures, including (a) measures of consonant identification for CIS processors using different combinations of cutoff frequencies for the lowpass filters in the envelope detectors and the pulse rate for each of the electrodes, and (b) measures of consonant and vowel identification for CIS processors using a wide range of mapping functions. The consonants and vowels for these measures were presented in quiet and at the speech-to-noise ratios of +15 and +10 dB. Studies in the quarter also included measures of consonant identification for CIS processors using different resolutions of output mapping, to determine the minimum number of discrete output levels required for asymptotic performance (this study was inspired by recent results obtained with the SPEAK strategy, reported by Zeng and Galvin, "Amplitude mapping and phoneme recognition in cochlear implant listeners," *Ear and Hearing* 20: 60-74, 1999).
- Completion of current studies with subject NU-5, a recipient of bilateral CI24M implants (March 29 to April 1). These studies included evaluation of various processing strategies designed to exploit bilateral implants.
- Discussions with Paul Carter from Cochlear Corporation, during a visit by him to RTI on June 23.
- Development of an Access database of processor designs and studies, to bring this information together in one place for fast access and in a structure that will provide responses to queries about prior designs and studies.
- Participation by Finley in a workshop on the new interface system designed by Advanced Bionics and the House Ear Institute, for laboratory control of the implanted receiver in the Clarion device (April 9-11).
- A visit by Oguz Poroy, of the University of Arkansas at Little Rock, for evaluation by Finley of a laboratory processor system developed by Oguz under the supervision of Philip Loizou, for future studies with implant patients at the University of Arkansas (May 5-7).
- Participation by Wilson, as the Guest of Honor, in the 5th *International Cochlear Implant Workshop* and 1st *Auditory Brainstem Implant (ABI) Workshop*, Würzburg, Germany (June 30 to July 4).
- Presentation of project results in three invited lectures at the Würzburg Workshops.
- Preparation for studies with patients having bilateral COMBI 40+ implants, from the University Hospital in Würzburg. This preparation included interviews with prospective subjects during and after the Würzburg Workshops, and screening tests with several prospective subjects during the week after the Workshops. The screening tests included

measures of electrode ranking (according to pitch percepts) within and across the two sides. These tests were conducted by Stefan Brill, in anticipation of his future work as a full-time member of our team (see Announcements section of this report).

- Preparation for Marian Zerbi's departure as a full-time member of the team. This preparation included seminars to transfer knowledge about processor specifications, real-time software for implementing processor designs, and software for various psychophysical tests to Finley, Lawson and Wilson. (Zerbi will continue as a consultant for the project after she leaves RTI.)
- Interviews with candidates to replace Zerbi and to fill an Audiologist position on the team.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

In this report we present results from studies with Ineraid subjects SR2 and SR9 to evaluate effects of manipulations in mapping functions for CIS processors. Results from other studies indicated above will be presented in future reports.

II. Effects of manipulations in mapping functions on the performance of CIS processors

One among many parameters that might affect the performance of CIS processors is the shape of the mapping function used to compress the relatively wide dynamic ranges of envelope signals into the relatively narrow dynamic ranges of electrically-evoked hearing. Various studies have been conducted by our group and others over the years to investigate effects of changes in the amount of compression and of changes in the endpoints of the mapping function (see, *e.g.*, Boëx *et al.*, 1997; Boëx-Spano, 1995; Cosendai and Pelizzone, 1997; Delhorne *et al.*, 1996; Eddington *et al.* 1996; and Pelizzone *et al.*, 1997). The studies have included experiments to identify the most important regions of the mapping function for speech reception. In broad terms, the results have shown or suggested that (a) the upper part of the mapping function, corresponding to relatively high envelope signals and relatively high loudnesses, is more important than the lower part of the mapping function, (b) clipping of relatively high envelope signals should be strictly avoided, (c) relatively weak consonant sounds such as the bursts of plosives need to be mapped well above auditory threshold in order to be recognized in a speech context, and (d) manipulations in the amount of compression produce results that often depend on the subject and the tests used to evaluate speech reception performance. In some cases, manipulations over a wide range exert almost no effect on speech reception scores, whereas in other cases, with other subjects or other tests, the same manipulations can produce large differences in scores.

Recently, Fu and Shannon have published results from a study in which effects of changes in the amount of compression were evaluated in tests with three subjects (Fu and Shannon, 1998). The subjects were users of the Nucleus-22 implant. They listened to simulations of 4-channel CIS processors whose outputs were presented to the transmitting coil of the Nucleus implant with a custom interface system. The exponent in the power function used for mapping was varied in nine steps from a highly compressive mapping (exponent of 0.05) to an almost linear mapping (exponent of 0.75). They found only a mild dependence of performance on the value of the exponent over a broad range of exponents (exponents from 0.1 to 0.5 for consonant identification, and exponents from 0.1 to 0.75 for vowel identification).

This result was somewhat surprising to us, so we undertook a similar study using subjects with percutaneous access to their electrode arrays. The tests with one of our two subjects also included presentations of speech tokens in conjunction with noise, allowing us to evaluate possible interactions between manipulations in the mapping function and the speech-to-noise ratio of the test items.

Methods

Ineraid subjects SR2 and SR9 participated in the present studies. SR2 enjoys extremely good results with his implant and a CIS processor, whereas SR9 has much lower speech reception scores with her implant and a CIS processor. Both are highly experienced subjects and both have used their CIS processors for many years.

The mapping function used in standard implementations of CIS processors is of the form

Output current = $A * \log(\text{envelope signal}) + k$,

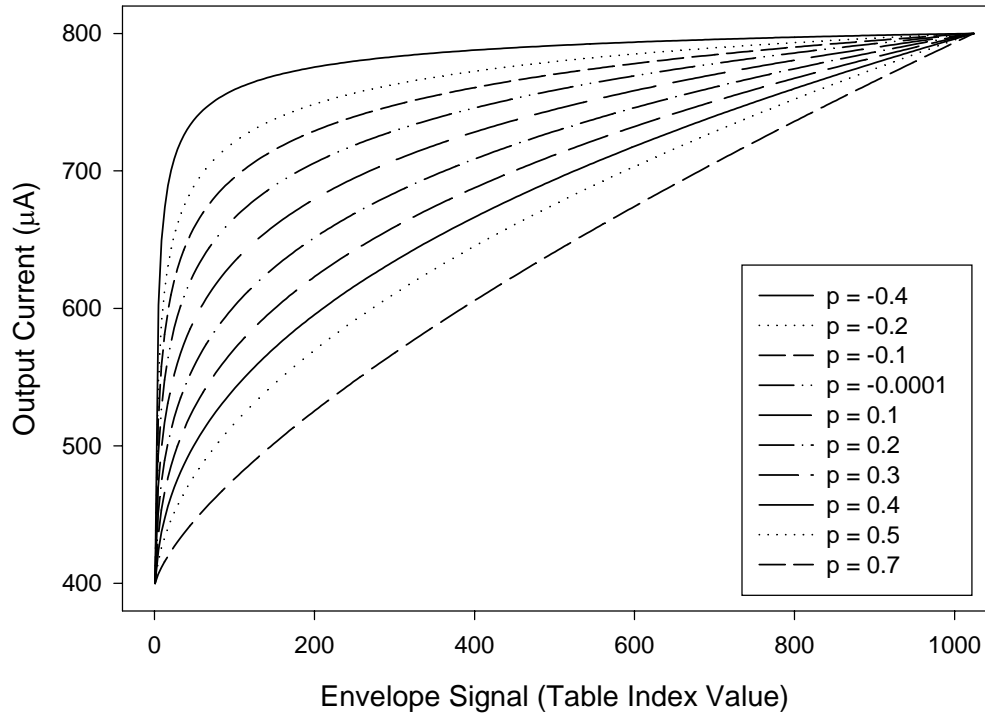


Fig. 1. Mapping functions used in the RTI study.

where A and k are adjusted so that the minimum envelope signal produces a threshold-level pulse and so that the maximum envelope signal produces a pulse that evokes an auditory percept at a "most comfortable loudness" (MCL).

A variation of the above function allows changes in the amount of compression. This variation is of the form

$$\text{Output current} = A * (\text{envelope signal})^{\text{exponent}} + k,$$

where again A and k are adjusted so that the minimum pulse amplitude corresponds to auditory threshold and the maximum pulse amplitude corresponds to a percept at MCL.

The second form of mapping functions was used in the present study. A graph of the functions for various exponents is presented in Fig. 1. These examples were derived with a threshold value of 400 µA and a MCL value of 800 µA. The exponents ranged from a highly-compressive -0.4 to an almost-linear 0.7. The function produced with the exponent of -0.0001 closely approximates the logarithmic mapping used in standard CIS processors.

All processors for subject SR2 used four channels, whose outputs were delivered to the four most-apical electrodes in SR2's implant. Additional parameters that were held constant across processors included 12th order bandpass filters, a 350 to 9500 Hz range of frequencies spanned by the bandpass filters, half wave rectifiers in the envelope detectors, 8th order lowpass filters with a corner frequency at 160 Hz in those detectors, a pulse rate of 500 pulses/s/electrode, a pulse

duration of 18 μ s/phase, and a "staggered" sequence of electrode stimulation. Most of these parameters were selected to approximate or match those used in the Fu and Shannon study. One exception was the pulse duration, which was much shorter in our study. The choice of a reduced number of channels for subject SR2 also was made to reduce his overall level of performance to a sensitive range for speech reception measures.

All processors for subject SR9 used six channels, whose outputs were delivered to the six intracochlear electrodes in her Ineraid implant. The order of the bandpass filters, the range of frequencies spanned by the filters, the characteristics of the lowpass filters in the envelope detectors, and the update order were the same as those used in the processors for SR2. The pulse rate used for SR9 was 417 pulses/s/electrode, and the pulse duration used for SR9 was 33 μ s/phase. In addition, a full wave rectifier was used in the envelope detectors. The choices of channel number, pulse rate, and pulse duration for SR9 were made to obtain an overall level of performance in a sensitive range for speech reception measures.

The exponent in the mapping function was varied between -0.4 and 0.7 in ten processors tested with SR2 and in six processors tested with SR9.

The processors for both subjects were evaluated with our standard test of consonant identification, with each of the consonants presented in an /a/-consonant-/a/ context in randomized orders and with multiple exemplars from one male and one female talker. Twenty four different consonants were used in the tests with SR2, and 16 were used in the tests with SR9. The higher number was used for SR2 to bring his scores down into a sensitive range. All tests were conducted with hearing alone, and no feedback was given as to correct or incorrect responses. At least 10 replications of each consonant were used in the test for each condition and for each of the talkers.

The consonants were presented in quiet for both subjects and also in noise for subject SR2. CCITT noise was used, which has a spectrum that matches the long-term spectrum of speech. The additional conditions for SR2 included the speech-to-noise ratios of +15 and +10 dB.

The processors for SR2 also were evaluated with tests of vowel identification in a /h/-vowel-/d/ context. Multiple exemplars of each of eight vowels recorded from a male talker were included in these tests. As with the consonant tests, the vowel tests used randomized orders and were conducted with hearing alone and no feedback as to correct or incorrect responses. The vowel tests included presentation of the vowels in quiet and at the speech-to-noise ratios of 15 and 10 dB. Fifteen replications of each vowel were used in the test for each condition.

Results

Percent-correct scores for consonants. Percent-correct scores from the tests of consonant identification are presented in Figs. 2 and 3. Figure 2 shows the scores on a scale of 0 to 100, and Fig. 3 shows the scores on a scale of 40 to 90. Scores for subject SR2 are presented in the left column of each figure, and scores for SR9 are presented in the right column.

The data for each condition (talker and speech-to-noise ratio) and subject were evaluated for significant differences among exponent conditions using one-way ANOVAs. The results for SR2 are presented in Table 1, and the results for SR9 are presented in Table 2. The tables also show the findings from *post hoc* comparisons for conditions that produced a significant ANOVA. Two *post hoc* tests were used, the conservative Tukey test and the less-conservative Fisher Least Significant Difference (Fisher LSD) test.

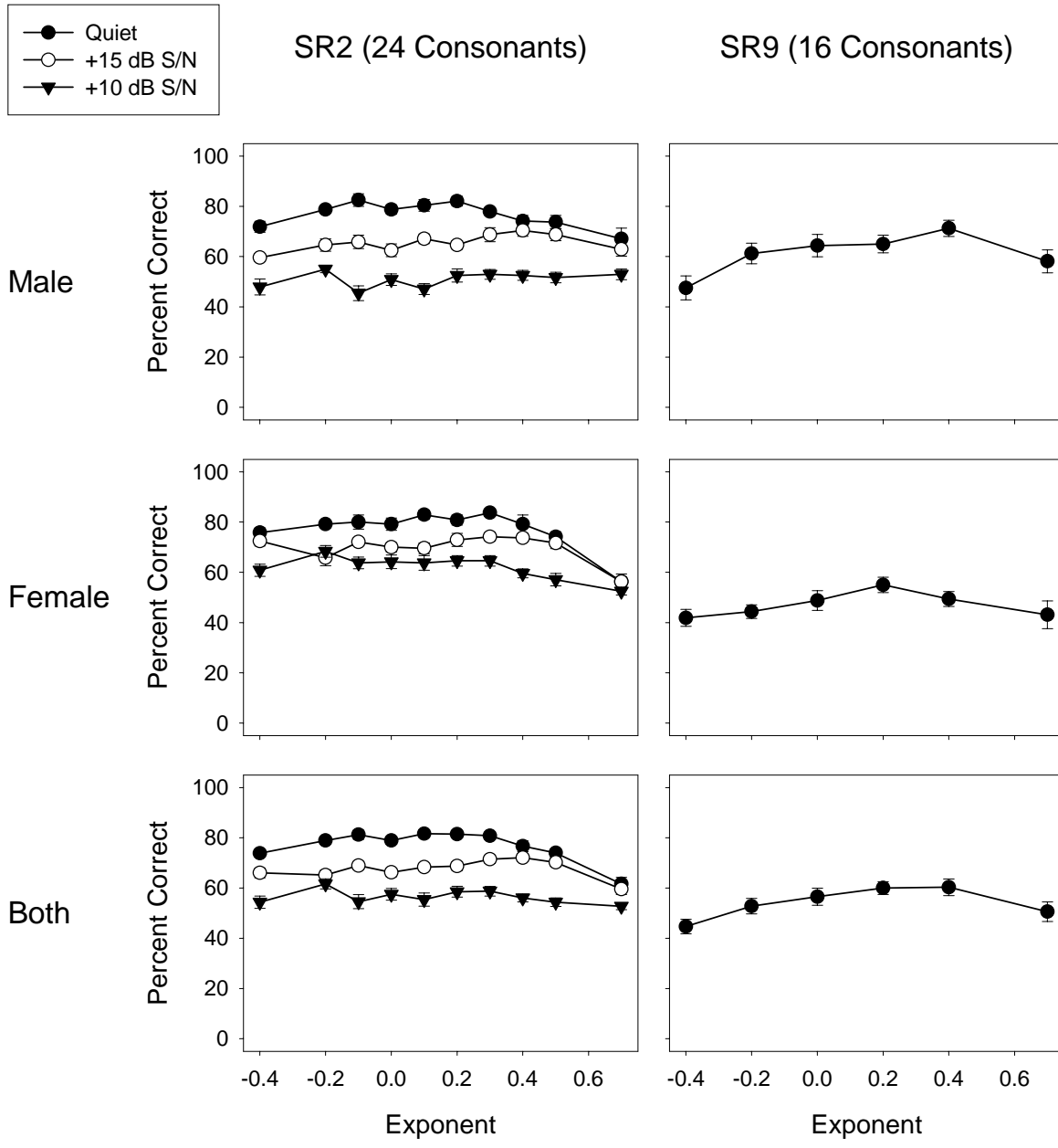


Fig 2. Consonant identification for various exponents in the mapping function used for CIS processors, subjects SR2 and SR9. The exponent of -0.4 produces a highly compressive mapping function, and the exponent of 0.7 produces an almost-linear function (see Fig. 1). The exponent of -0.0001 produces a function that closely approximates the logarithmic function used in standard CIS processors.

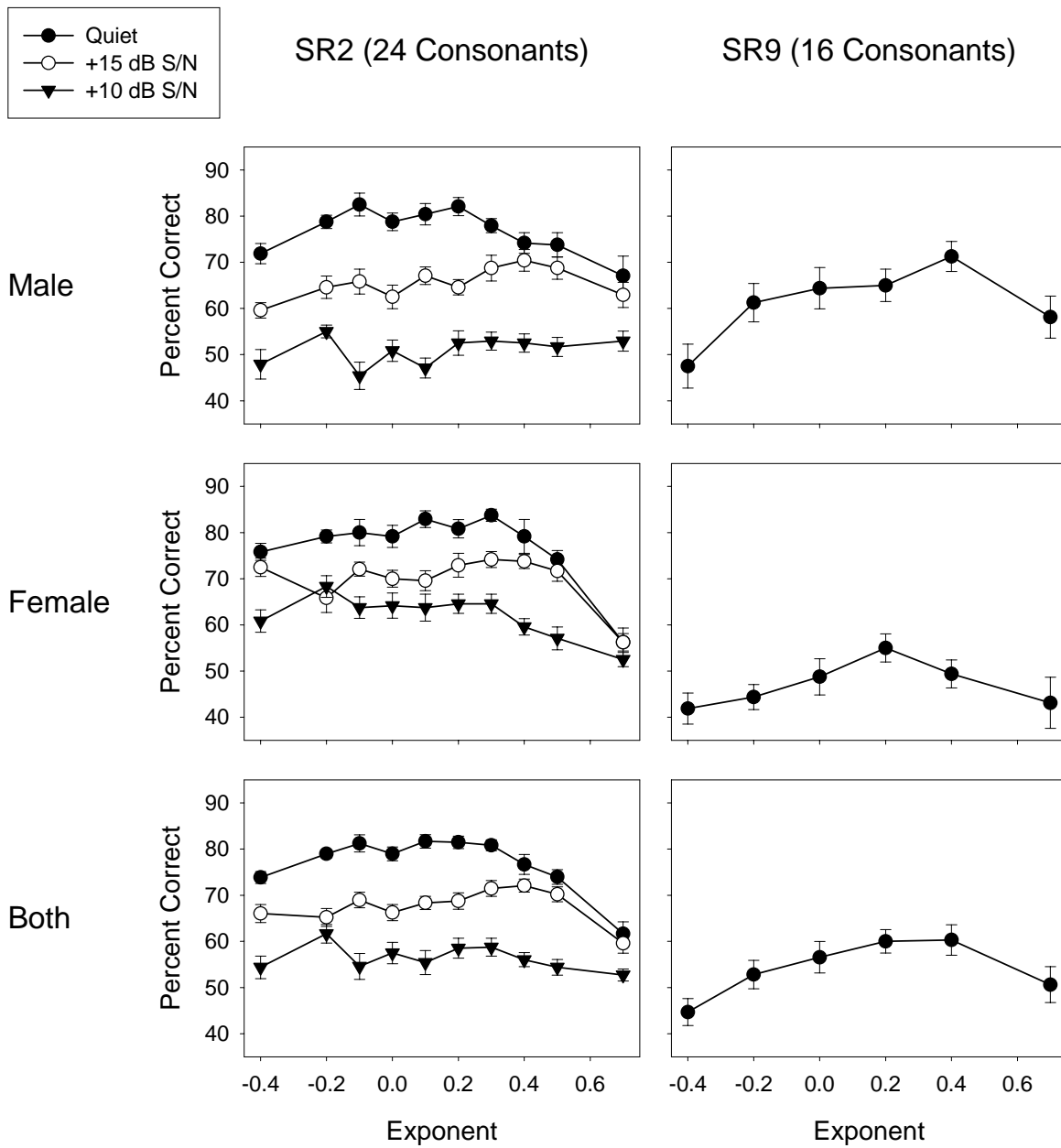


Fig. 3. Same as Fig. 2, but with a different scale for percent correct.

Table 1. ANOVA and *post hoc* comparisons among percent correct scores for subject SR2.

Speaker	S/N	ANOVA	<i>Post hoc</i> test	Significant differences (numbers refer to exponents)
Male	inf	$p < 0.001$	Tukey	-0.1 and 0.2 > 0.7, -0.4 0.1 > 0.7
	+15	$p = 0.048$		0.4 > -0.4
	+10	NS		
Female	inf	$p < 0.001$		-0.4 through 0.5 > 0.7
	+15	$p < 0.001$		-0.4 and -0.1 through 0.5 > 0.7
	+10	$p < 0.001$		-0.2 through 0.3 > 0.7 -0.2 > 0.5
Both	inf	$p < 0.001$		-0.4 through 0.5 > 0.7 -0.1 and 0.1 through 0.3 > -0.4 0.1 > 0.5
	+15	$p < 0.001$		-0.1 and 0.1 through 0.5 > 0.7
	+10	NS		
Male	inf	$p < 0.001$	Fisher LSD	-0.2 through 0.3 > 0.7 -0.2 through 0.2 > -0.4 -0.1 and 0.2 > 0.4, 0.5
	+15	$p = 0.048$		0.3 through 0.5 > -0.4 0.4 > -0.0001, 0.7
	+10	NS		
Female	inf	$p < 0.001$		-0.4 through 0.5 > 0.7 0.1 through 0.3 > 0.5 0.1 and 0.3 > -0.4
	+15	$p < 0.001$		-0.4 through 0.5 > 0.7 -0.4 and 0.2 through 0.4 > -0.2
	+10	$p < 0.001$		-0.4 through 0.4 > 0.7 -0.2 through 0.3 > 0.5 -0.2 > 0.4, -0.4
Both	inf	$p < 0.001$		-0.4 through 0.5 > 0.7 -0.2 through 0.3 > -0.4, 0.5 0.1 and 0.2 > 0.4
	+15	$p < 0.001$		-0.4 through 0.5 > 0.7 0.3 through 0.5 > -0.2 0.3 and 0.4 > -0.4, -0.0001
	+10	NS		

Table 2. ANOVA and *post hoc* comparisons among percent correct scores for subject SR9.

Speaker	S/N	ANOVA	<i>Post hoc</i> test	Significant differences (numbers refer to exponents)
Male	inf	$p = 0.006$	Tukey	0.4 and 0.2 > -0.4
Female		NS		
Both		$p = 0.006$		0.4 and 0.2 > -0.4
Male		$p = 0.006$	Fisher LSD	-0.2 through 0.4 > -0.4 0.4 > 0.7
Female		NS		
Both		$p = 0.006$		0.4 and 0.2 > -0.4, 0.7 -0.0001 > -0.4

In general, the percent-correct scores are relatively uniform over wide ranges of exponent values for both subjects. For presentation of the consonants in quiet, the ANOVAs and *post hoc* Tukey tests show that exponents in the range of -0.2 to 0.4 usually produce scores that are not significantly different from each other, for all talker conditions and each subject. In most cases, the best score (obtained with an exponent in the range of -0.1 to 0.4) is significantly greater than the score or scores at one or both of the extremes.

For SR2, exponents of -0.1 and 0.2 produced significantly higher scores for the male talker than the exponents at the extremities, -0.4 and 0.7. Also, the exponent of 0.1 produced a higher score than the exponent of 0.7. For the female talker, all exponents from -0.4 through 0.5 produced higher scores than the exponent of 0.7. This also was the case for the combined talkers. In addition, the exponent of -0.1, and the exponents from 0.1 through 0.3, produced higher scores than the exponent of -0.4. The exponent of 0.1 produced a higher score than the exponent of 0.5 for the combined talkers as well.

For SR9, exponents of 0.2 and 0.4 produced significantly higher scores for the male talker than the exponent of -0.4. Differences among scores for the female talker were not significant. Scores for the combined talkers showed the same pattern as that found for the male talker, *i.e.*, the scores obtained with the exponents of 0.2 and 0.4 were significantly higher than the score obtained with the exponent of -0.4.

The region of highest scores for SR2 included the exponent value approximating the standard mapping function (exponents in the region of -0.0001). The highest scores for SR9, on the other hand, were obtained for less-compressive mapping functions, with exponents in the range of 0.2 to 0.4.

Results from the tests with SR2 involving presentation of the consonants in noise were somewhat different from the results obtained for presentation of the consonants in quiet. For the male talker and the +15 dB S/N, the exponent of 0.4 produced a higher score than the exponent of -0.4. For the female talker, all exponents from -0.4 through 0.5, except for the exponent of -0.2, produced higher scores than the exponent of 0.7. For combined speakers, the exponent of -0.1, and the exponents from 0.1 through 0.5, produced higher scores than the exponent of 0.7.

For the +10 dB S/N conditions, no significant differences were found among the scores for the different exponents either for the male talker or for the combined talkers. For the female talker, the exponents from -0.2 through 0.3 produced higher scores than the exponent of 0.7. In addition, the exponent of -0.2 produced a higher score than the exponent of 0.5.

An interesting aspect of the results for the quiet and +15 dB S/N conditions is that the curves for both talkers do not differ significantly over the range of exponent values from 0.4 to 0.7. The scores are relatively high with the 0.4 exponent. These observations suggest that a choice of a 0.4 exponent might be advantageous for listening to speech at speech-to-noise ratios of +15 dB or higher. This also would not be a bad choice for more adverse speech-to-noise ratios, inasmuch as the results for the +10 dB S/N conditions either show no dependence of scores on the choice of exponent (male and combined speakers) or only a weak dependence (female speaker). In the case of the weak dependence, the exponent of 0.4 does not produce a significant decrement in performance compared with the highest performance among exponent choices (exponent of -0.2), at least according to the Tukey tests. (The Fisher LSD tests do indicate a significant difference in scores for the -0.2 and 0.4 exponents.)

Feature-transmission scores for consonants. Figures 4 and 5 show feature-transmission scores for the consonant tests conducted with subjects SR2 and SR9, respectively. For subject SR2, the scores for overall information transmission, voicing and manner of articulation are quite similar over the tested range of exponent values, for all talker and speech-to-noise conditions. Transmission of manner information appears to be somewhat more susceptible to noise interference than voicing or overall information, but the curves for the three features are still similar at the speech-to-noise ratio of +10 dB.

In contrast, scores for the transmission of information as to place of articulation are much lower than the scores for the other features shown, for all talker and speech-to-noise conditions. (Relatively low scores for transmission of place information is a common finding with implant subjects.) The shapes of the curves for the place scores are quite similar to those for the percent-correct scores (compare Fig. 4 with Fig. 3 or Fig. 2).

Results for SR9 show a relatively high transmission of voicing information for exponent values of -0.0001 and higher for the male talker, and for exponent values of -0.2 and higher for the female talker and for the combined talkers. The scores for overall information transmission and for manner are similar to each other over the tested range of exponent values. As with SR2, scores for transmission of place information are lower than the other scores over the tested range, and the shape of the curves for place are quite similar to the shapes of the curves for the percent-correct scores.

Percent-correct scores for vowels. Results from the tests of vowel identification with SR2 are presented in Fig. 6. Note that the number of exponent values included in these tests is smaller than the number included in the consonant tests for this subject. Three values were included in the vowel tests for the quiet and +15 dB conditions, and five values were included in the tests at the +10 dB speech-to-noise ratio.

The scores across exponent values are relatively uniform for presentation of the vowels in quiet and for each of the speech-to-noise ratios. Indeed, neither the ANOVA for quiet, nor the ANOVAs for vowels with noise, indicated a significant difference among scores for the different exponent values.

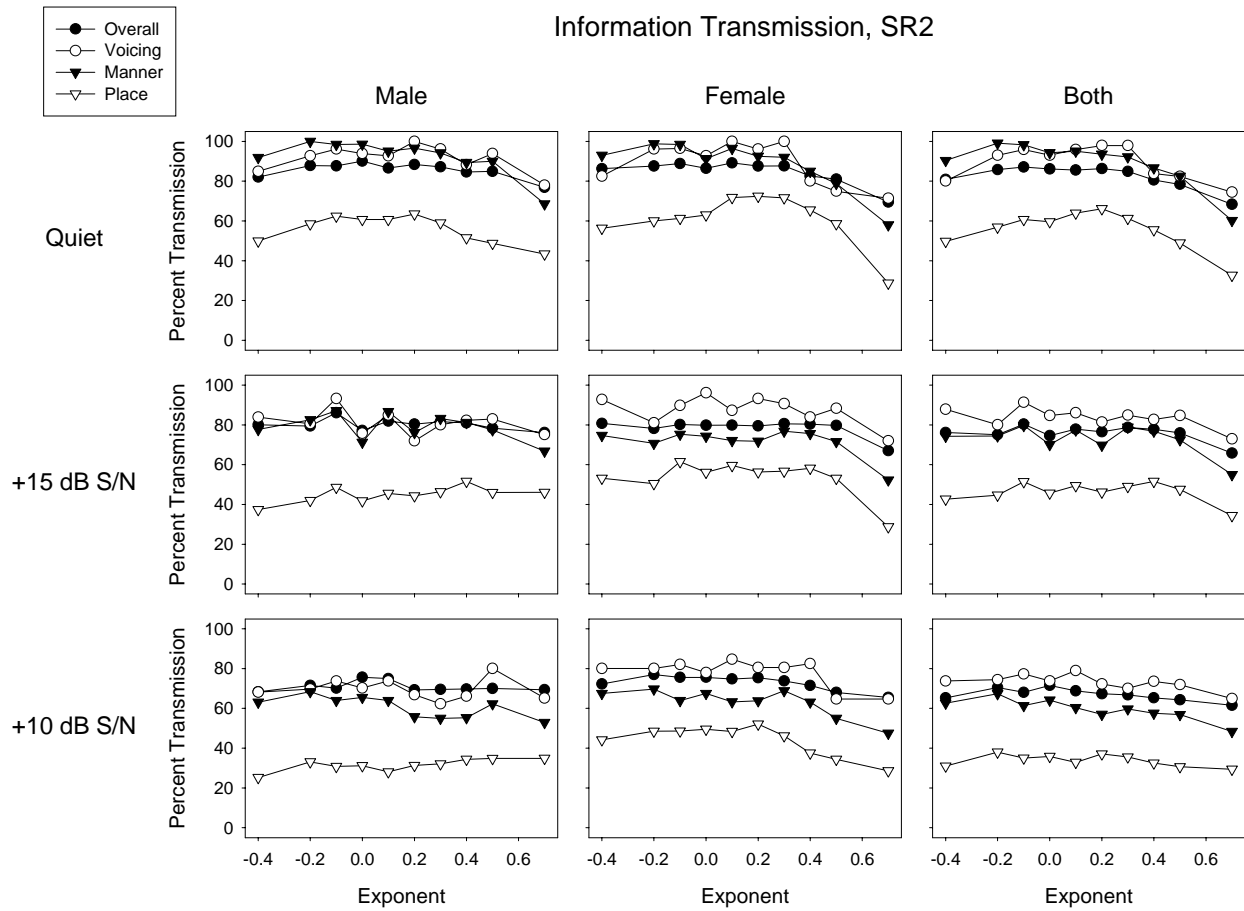


Fig. 4. Feature transmission scores from the tests of consonant identification with subject SR2.

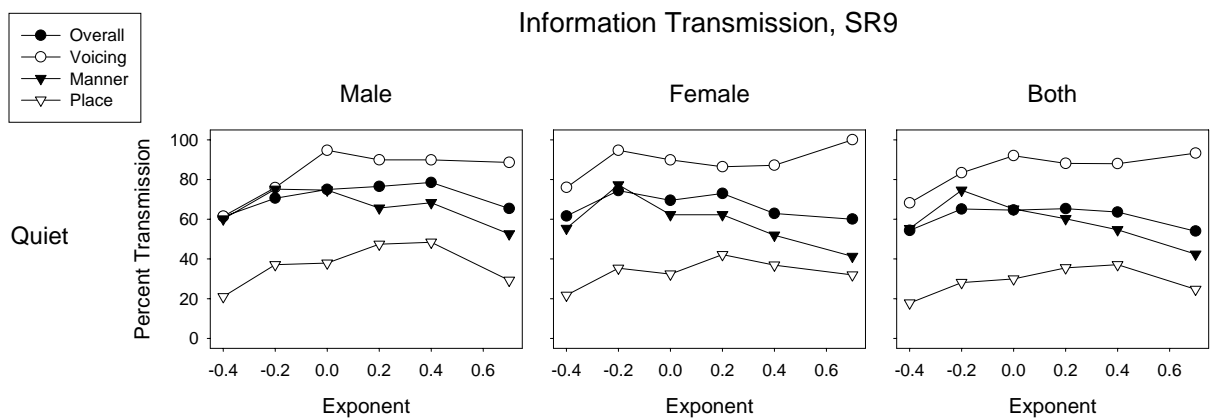


Fig. 5. Feature transmission scores from the tests of consonant identification with subject SR9.

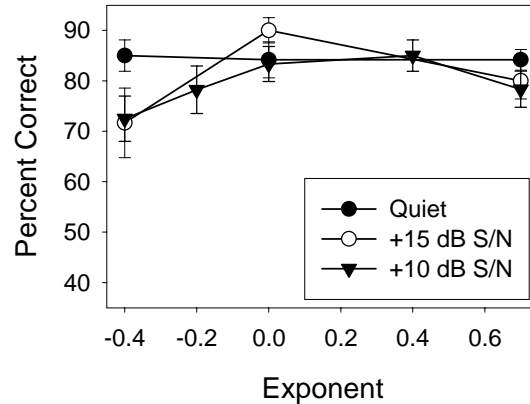


Fig. 6. Vowel identification for various exponents in the mapping function used for CIS processors, subject SR2.

Comparisons with findings from other laboratories

Fu and Shannon. As noted before, Fu and Shannon recently have published results from a study to evaluate effects of manipulations in mapping functions for cochlear implant speech processors (Fu and Shannon, 1998). A graph of the mapping functions used in that study is presented in Fig. 7. (These curves also were derived with a threshold value of 400 μ A and a MCL value of 800 μ A.) The range of exponent values used by Fu and Shannon produces a set of functions that are similar to the set used in our study (compare Figs. 7 and 1). The exponents themselves are quite different from ours, because their functions map envelope values from 0 to 1000, whereas ours map envelope values from 1 to 1024. The starting value for envelope strongly affects the values of A and k in the mapping function equation (see page 6), and this in turn produces quite different curves for the same exponent value.

Mapping functions corresponding to the highest and lowest exponents in each of the studies are shown in Fig. 8. As is evident from the figure, the overall ranges of functions for the two studies approximate each other. The most compressive function used by Fu and Shannon is somewhat more compressive than the most compressive function used in our study. The least compressive functions for the two studies almost overlie each other.

Fu and Shannon used 4 channel CIS processors, as implemented in custom software and with use of their research interface for laboratory control of the Nucleus CI22 implant. Three subjects with this implant participated in the studies. The overall range spanned by the bandpass filters was 100 to 6000 Hz, compared with the range of 350 to 9500 Hz in our study. Stimuli were directed to monopolar electrodes in the Ineraid implant in our study, and to bipolar pairs of electrodes in the Nucleus implant in the Fu and Shannon study (a "BP+1" configuration was used, involving electrodes separated by 1.5 mm from center to center along the electrode array). With the exception of pulse duration, other parameters were identical between the processors used for SR2 in our study and the processors used for the three subjects in the Fu and Shannon study. The processors used for SR9 in our study had six channels, full wave rectifiers, and a pulse rate and phase duration that were somewhat different from those used in the processors for the Fu and Shannon study. In general, the processors were similar but not identical across the two studies.

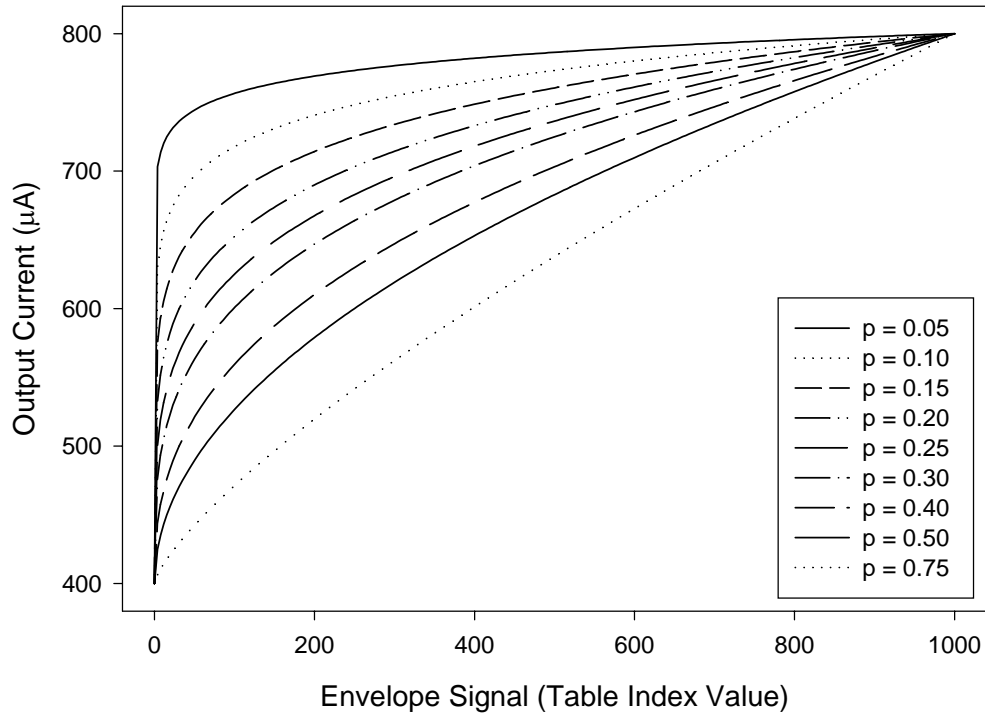


Fig. 7. Mapping functions used in the Fu and Shannon study.

Figure 9 shows the percent-correct scores from the tests of consonant identification conducted by Fu and Shannon. The exponents are plotted along both linear (left panel) and logarithmic (right panel) scales. Fu and Shannon presented the logarithmic plot in their paper, but plots with a linear scale facilitate comparisons between the Fu and Shannon results and our results, which are plotted along a linear scale.

Figure 9 shows decrements in performance at the extremities of the exponent values, similar to our results, for speech presented in quiet. The statistical uncertainty is relatively high in much of the Fu and Shannon data (compare Fig. 9 with Fig. 2), perhaps due both to the use of multiple subjects and the use multiple talkers. Fu and Shannon did not evaluate effects of noise in their initial study with implant patients, but speculated that mapping functions with exponents higher than 0.2 (*i.e.*, less compressive than the best function in their data for quiet) might be helpful for listening to speech in noise. The speculation was based on results from acoustic simulation studies, using subjects with normal hearing.

Figure 10 shows feature transmission scores for the Fu and Shannon study. They plotted scores for voicing, manner and place. As in our results, the scores for transmission of place information are lower than the scores for transmission of manner or voicing information (compare Fig. 10 with Figs. 4 and 5). Unlike our results, the Fu and Shannon results indicate lower scores for the transmission of voicing information than for the transmission of manner information at low exponent values (exponent values below 0.4 in Fig. 10).

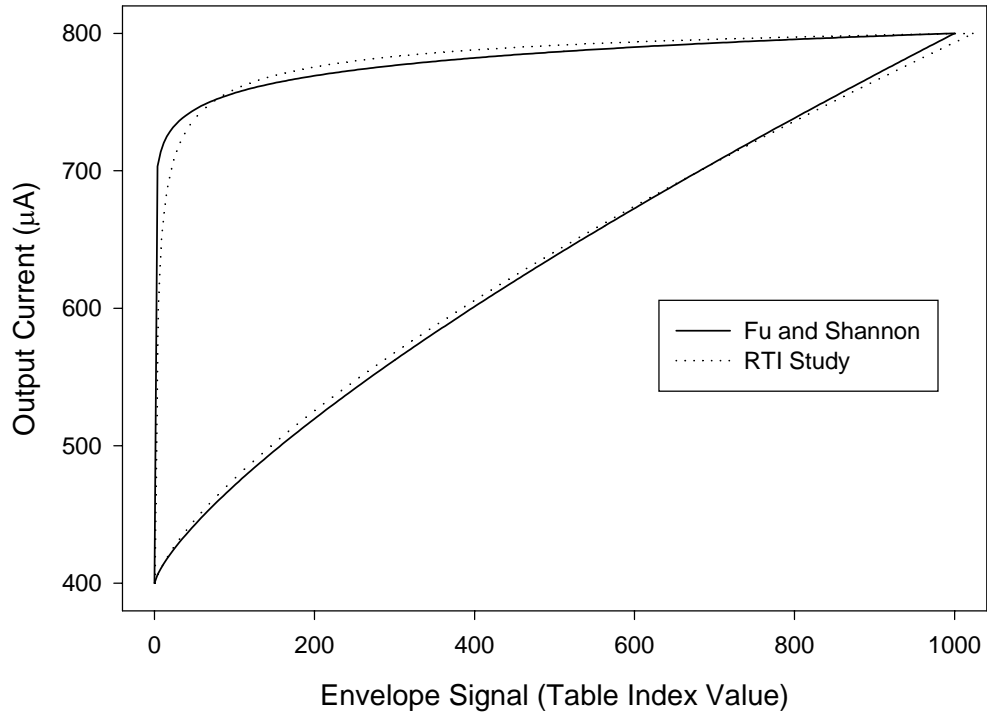


Fig. 8. Mapping functions with lowest and highest exponents, Fu and Shannon study (solid lines) and RTI study (dotted lines).

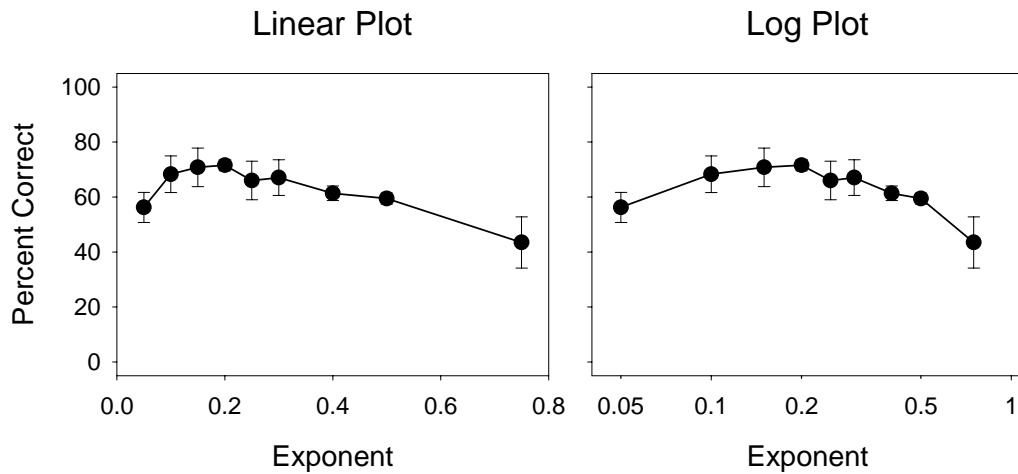


Fig. 9. Percent-correct scores from tests of consonant identification in the study conducted by Fu and Shannon (1998). The exponents used in the study are shown along both linear (left panel) and logarithmic (right panel) scales. The tests included 16 consonants presented in an /a/-consonant-/a/ context.

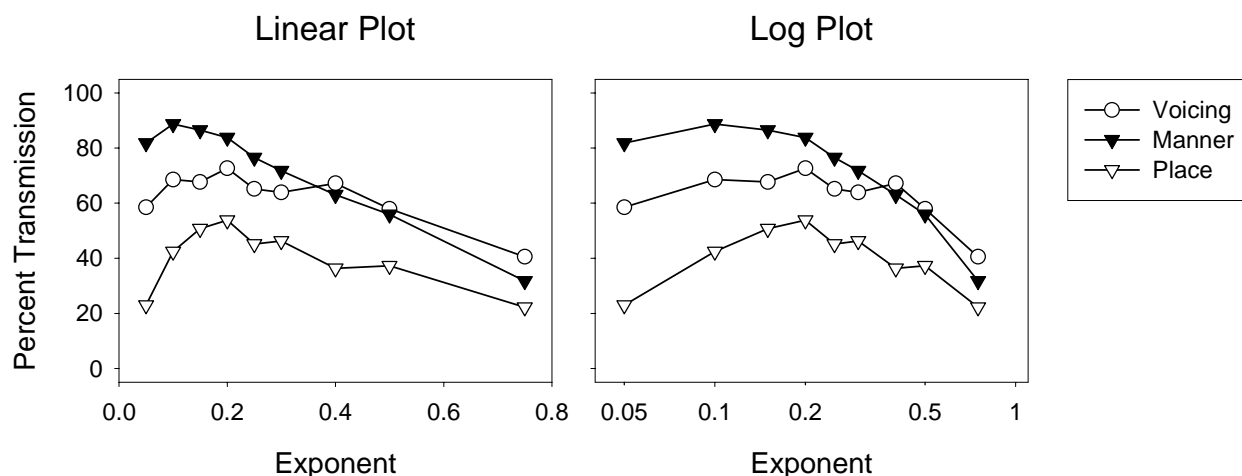


Fig. 10. Feature-transmission scores from the study conducted by Fu and Shannon (1998). The exponents used in the study are shown along both linear (left panel) and logarithmic (right panel) scales.

The Fu and Shannon results also show a correspondence between the shape of the curve for place transmission and the shape of the curve for percent-correct scores (compare Figs. 10 and 9). The maximum in the curve for place is somewhat "sharper" (more peaked) than in the curve for percent correct in the Fu and Shannon results. The shapes of the curves are more similar in our data.

Most recently, Fu and Shannon have extended their initial studies to include presentation of consonants and vowels in noise (Fu and Shannon, 1999). The three subjects who participated in the initial studies also participated in these subsequent studies. The processors were the same as those of the initial studies except that a BP+5 configuration was used for the electrodes (with the two electrodes of each bipolar pair separated by 4.5 mm). The noise used was an approximation to speech-spectrum noise, derived by filtering wide-band (spectrally flat) noise with a first-order lowpass filter that had a corner frequency at 800 Hz.

The principal results from the subsequent studies are presented in Fig. 11. (Only the averages of the percent-correct scores across the three studied subjects are shown, in that error bars were not reported by Fu and Shannon.) As in our results for subject SR2, manipulation of the exponent over a broad range has almost no effect on the identification of vowels in quiet. Also, the addition of noise, even at the high levels used by Fu and Shannon (+6 and 0 dB speech-to-noise ratios), produces only relatively small decrements in vowel identification, especially for high values of the exponent.

Results from the tests of consonant identification also are broadly similar to our results with subject SR2 (compare the right panel of Fig. 11 with the left column of Fig. 2). In quiet, performance declines in both sets of results with use of the least-compressive mapping function. In noise, scores are more similar between the least-compressive mapping function and somewhat more-compressive functions. For the relatively adverse speech-to-noise ratios used in the Fu and Shannon study, consonant identification is maximized across the quiet and speech-in-noise

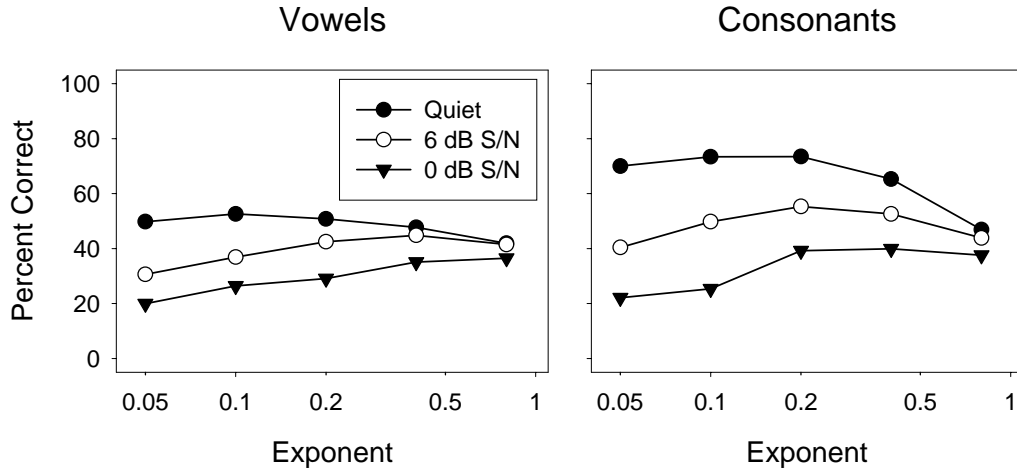


Fig. 11. Percent-correct scores from an additional study conducted by Fu and Shannon (1999), that included presentation of vowels and consonants in noise. Exponents are shown along a logarithmic scale only. The vowel tests included 12 vowels presented in a /h/-vowel-/d/ context, and the consonant tests included 16 consonants presented in an /a/-consonant-/a/ context.

conditions with the exponent of 0.2. That exponent produces a mapping function that approximates the mapping function used in standard CIS processors (the curve for the 0.2 exponent in Fig. 7 is similar to the curve for the -0.0001 exponent in Fig. 1).

Boëx and coworkers. Boëx and coworkers also have conducted a study to evaluate effects of changes in the mapping function on the performance of CIS processors. The principal results are presented in Fig. 12 (data from Boëx, 1995). The three subjects were long-term users of the Ineraid device. CIS processors were used, with five channels and a relatively high pulse rate, 2000 pulses/s/electrode. As in our study, monopolar coupling was used. The mapping functions, and the dependence of the mapping functions on the value of the exponent, were similar to ours.

Results from the consonant tests (left panel of Fig. 12) show gradual decrements in performance with increases in exponent value for subject BR, a shallow peak in performance at the exponent of 0.3 for subject LW, and a plateau in performance with exponents of 0.5 and higher for subject JG. The patterns of scores across exponent values for subjects LW and JG are somewhat similar to the overall pattern observed with our subject SR9. For these subjects, a peak or plateau in performance is found at exponent values in the range of 0.2 to 0.5. In contrast, the pattern for subject BR is somewhat similar to the overall pattern observed with our subject SR2. This pattern is one of relatively uniform performance for exponents in the range of -0.2 to about 0.5, and of lower performance at higher values of the exponent.

The results for vowel identification (right panel of Fig. 12) differ from the results for consonant identification for two of the subjects in the Boëx study. Consonant scores for subject LW indicate a peak in performance at the exponent value of 0.3, but the vowel scores indicate monotonic increases in performance with increases in exponent values up to the tested limit of 0.9. Consonant scores for subject JG show a plateau in performance at and above the exponent value of 0.5, but the vowel scores indicate improvements in performance with increases in

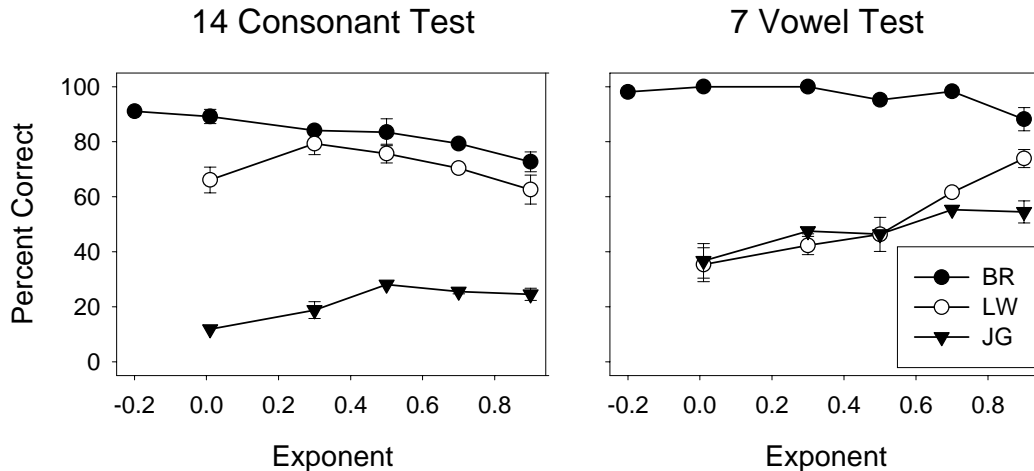


Fig. 12. Percent-correct scores from the study conducted by Boëx (1995). Scores for each of the three subjects are indicated by the different symbols. The consonant tests included presentation of 14 French consonants in an /a/-consonant-/a/ context, and the vowel tests included presentation of 7 French vowels in isolation, without bracketing consonants.

exponent values beyond 0.5. Scores for subject BR are relatively uniform across exponent values, as in our results for subject SR2 (Fig. 6) and as in the results for the three subjects studied by Fu and Shannon (see, *e.g.*, the data for the quiet condition in the left panel of Fig. 11).

Loizou and Poroy. Results from the recent study of Loizou and Poroy (1999) are presented in Fig. 13. Six subjects participated in this study. All were users of CIS-Link processors in conjunction with their Ineraid implants. A separate laboratory system was used to implement CIS processors for the tests of Fig. 13. The processors for each subject used six channels, a pulse rate of 800 pulses/s/electrode, a pulse duration of 40 μ s/phase, and a staggered update order. As in our study and in the study of Boëx and coworkers, monopolar coupling was used. The dependence of the mapping functions on the value of the exponent was identical to that in our study (see Fig. 1). Exponents used in the study of Loizou and Poroy included -0.1, -0.0001, 0.2 and 0.6.

The results show equivalent performance for the exponents of -0.1, -0.0001 and 0.2. Use of the highest exponent, 0.6, produced a decrement in performance. This pattern is similar to the pattern observed in our study for subject SR2, and to the pattern observed by Fu and Shannon for their three subjects. Performance is relatively uniform over a broad range centered on the default value for CIS processors, and performance drops with use of exponents that produce more linear mapping functions. The exponents used in the study of Loizou and Poroy did not include those that would produce highly-compressive mapping functions, *i.e.*, exponents of -0.2 and lower. Such exponents produced decrements in performance compared with the best performance both in our studies and in those conducted by Fu and Shannon.

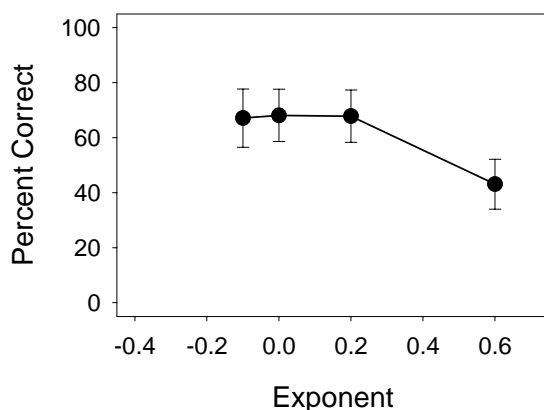


Fig. 13. Percent-correct scores for consonant identification in the study conducted by Loizou and Poroy (1999). The consonant tests included presentation of 20 consonants in a vowel-consonant-vowel context using each of three vowels (/i/, /a/ and /u/). The recorded tokens were produced by a female talker.

Discussion

Results from the present study, along with results from other studies, show that the performance of CIS processors can be relatively insensitive to manipulations in mapping functions over a rather broad range. That range usually includes the default mapping function for CIS processors, a logarithmic mapping function or a power function with an exponent of -0.0001. Typically, some range of higher and lower values of the exponent can support equivalent scores in tests of consonant identification. Beyond that range, which varies from subject to subject, consonant identification scores decline.

Some subjects show a peak or asymptote in performance at an exponent that is somewhat higher than the default value. In the studies to date, these subjects appear to be in the low- or mid-performance categories with their implants. Subject SR9 achieved her best scores with an exponent in the range of 0.2 to 0.4 in our studies, and subjects LW and JG achieved their best or asymptotic scores with exponents between 0.2 and 0.5 in the study conducted by Boëx and coworkers. The overall performance for each of these three subjects is substantially lower than that of SR2 in our study or of BR in the Boëx *et al.* study.

Results from our studies with subject SR2 also indicate that functions with less compression than the default function may be helpful for listening to speech in noise. The patterns of scores for quiet and for the speech-to-noise ratio of +15 dB suggest that an exponent of 0.4 may optimize consonant identification for speech-to-noise ratios of +15 dB or higher. Also, the choice of 0.4 may not be worse than other choices for more adverse speech-to-noise conditions. Our data do not support the initial suggestion offered by Fu and Shannon, that an even more linear mapping function might be helpful for listening to speech in noise. Increases in the exponent beyond 0.4 produced decrements in performance for SR2.

Results from the three subjects studied by Fu and Shannon also do not support the idea that almost-linear functions might be best for listening to speech in noise. Instead, the results show the best performance across the quiet, +6 dB speech-to-noise, and 0 dB speech-to-noise conditions with the exponent of 0.2 for their mapping functions, which produces a mapping function close to the present default mapping function for CIS processors.

Vowel identification in quiet was hardly affected by gross manipulations in the mapping functions for SR2 in our study, or for the three subjects in study conducted by Fu and Shannon. An improvement in vowel identification with increases in the exponent was observed for two of the three subjects studied by Boëx and coworkers. Results for the third subject were similar to those of SR2 in our study and the subjects in the Fu and Shannon study. The subjects in the Boëx *et al.* study who demonstrated improvements in vowel identification with increases in the exponent were members of the low- or mid-performance groups with their implants.

Results from our study and the Fu and Shannon study show that vowel identification is less susceptible to noise interference than consonant identification. Scores for our subject SR2 were not depressed even at the speech-to-noise ratio of +10 dB, and scores for the three subjects studied by Fu and Shannon were only somewhat depressed at the highly-adverse speech-to-noise ratio of 0 dB.

In summary, the present default mapping function appears to be a good choice for many subjects, including subjects at the high end of the performance spectrum. A somewhat less compressive function may well be helpful for other subjects, perhaps including those with relatively poor performance with their implants. A somewhat less compressive function also may be helpful to some subjects encountering a broad range of speech-to-noise ratios.

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III. Plans for the next quarter

Our plans for the next quarter include the following:

- Ongoing studies with subject SR2. We expect that studies for the next quarter will include (a) completion of the "rate/LPF" matrix of conditions described in the Introduction to this report and (b) evoked potential studies aimed at evaluation of various strategies to replicate noninstantaneous compression functions found in normal hearing.
- Studies with Ineraid subject SR9, for the weeks beginning on August 2 and August 9. We expect that the studies will include (a) measures of consonant identification and sentence recognition for CIS processors using different combinations of cutoff frequencies for the lowpass filters in the envelope detectors and the pulse rate for each of the electrodes and (b) measures of consonant identification for CIS processors using a wide range of compression functions. Results from the studies with SR9 should complement results from recent similar studies with SR2, as SR9 has relatively poor performance with her implant and SR2 enjoys quite high levels of performance with his implant.
- A visit by Chris van den Honert, of Cochlear Corporation, to discuss details of upcoming cooperative studies involving new electrode designs (July 12).
- Continued development of the Access database mentioned in the Introduction, to bring together in a database format a complete record of speech processor designs and results for our laboratory.
- Initial entries into the database.
- Design of additional databases, for evoked potential studies and for psychophysical studies.
- Participation in the *1999 Conference on Implantable Auditory Prostheses*, to be held in Pacific Grove, CA, August 29 through September 3. The participation by the RTI team will include presentation of three invited lectures.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

IV. Announcements

We are pleased to announce that Robert Wolford has accepted a position on our team. Bob is an experienced audiologist with detailed knowledge of cochlear implants and tests used to evaluate the performance of implant systems. He received his MS in Audiology from the University of North Carolina in 1982. Since then he has worked as an audiologist at the University of North Carolina Hospital, Duke University Medical Center, the North Carolina Ear and Hearing Clinic, and with North Carolina Audiology Associates, Inc. He also served as the Acting Director of Audiology for several years at the DUMC, the Director of Audiology at the North Carolina Ear and Hearing Clinic, and the Director of the Cary, NC clinic for NC Audiology Associates. He is the first author or co-author for a dozen publications, most in the field of cochlear prostheses. He is a member of the American Speech, Language and Hearing Association, the American Academy of Audiology, and the North Carolina Speech, Language and Hearing Association.

Bob has worked with us on a part-time basis since 1986 in the conduct of various speech reception studies with our subjects. His time was supported through approved purchase order and consulting agreements. Happily, he will become a full-time member of the Center for Auditory Prosthesis Research beginning on August 1, 1999. At that time he will assume the major responsibility for speech reception studies in our laboratories. He also will conduct psychophysical studies, interpret and report results from psychophysical and speech reception studies, and work with Jeannie Cox in the development of databases containing conditions and results of psychophysical and speech reception studies.

We also are pleased to announce that Stefan Brill will begin a postdoctoral appointment in the Center beginning in the fall of 1999. The anticipated term of the appointment is two years.

Stefan presently is completing his Ph.D. at the University of Vienna, under the guidance of Erwin Hochmair at the University of Innsbruck, in cooperation with the University of Vienna. Stefan's thesis work is in the design and evaluation of speech processing strategies for cochlear prostheses. His experience includes work with implant patients, digital signal processing, programming of DSP chips, a wide range of additional programming languages, and teaching. He has presented papers at many international conferences on cochlear implants and related topics. He also recently published a paper in the American Journal of Otology on "Optimization of channel number and stimulation rate for the fast continuous interleaved sampling strategy in the COMBI 40+." He is a member of the International Functional Electrical Stimulation Society.

We expect that Stefan's main work with us will involve studies with recipients of bilateral implants. He will play a major role in upcoming studies with recipients of COMBI 40+ implants on both sides, in cooperation with the University Hospital in Würzburg, Germany, and with recipients of CI24M implants on both sides, in cooperation with the University of Iowa Hospitals and Clinics.

V. Acknowledgments

We thank subjects MI-5, SR2 and NU-5 for their participation in the studies of this quarter. We also are grateful to Stefan Brill, presently with the University of Innsbruck and soon to begin a postdoctoral appointment at RTI, for conducting screening studies in Würzburg with subjects having COMBI 40+ implants on both sides.

Appendix 1. Summary of reporting activity for this quarter

Reporting activity for this quarter, covering the period of April 1 through June 30, 1999, included the following invited lectures:

Wilson BS: Speech coding strategies. Presented at the *5th Int. Cochlear Implant Workshop* and *1st Auditory Brainstem (ABI) Workshop*, Würzburg, Germany, June 30 through July 4, 1999.

Lawson DT, Wilson BS: Experiments in bilateral implanted patients using the CIS strategy.

Presented by Wilson at the *5th Int. Cochlear Implant Workshop* and *1st Auditory Brainstem (ABI) Workshop*, Würzburg, Germany, June 30 through July 4, 1999.

Wilson BS: The future of cochlear implants. Presented at the *5th Int. Cochlear Implant Workshop* and *1st Auditory Brainstem (ABI) Workshop*, Würzburg, Germany, June 30 through July 4, 1999.