Seventh Quarterly Progress Report

April 1 through June 30, 2000

NIH Project N01-DC-8-2105

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 Ineraid subject SR3 during the periods from April 3 to April 14 and from May 9 to May 12. The studies included (1) measures of consonant identification and sentence recognition for CIS processors using a wide range of compression functions, (2) measures of consonant identification for processors using various combinations of pulse rate and envelope cutoff frequency, (3) measures of consonant identification, sentence recognition, and monosyllabic word recognition for CIS processors using various pulse rates and a fixed envelope cutoff frequency, and (4) evaluation of processors with high rate "conditioner" pulses in addition to the pulses conveying information.
- Studies with subject ME3, a recipient of Med El COMBI 40+ implants on both sides, during the two weeks beginning on May 22. The studies included measures of sensitivities to interaural timing and amplitude differences and evaluation of various processing strategies designed to represent cues for sound localization or to exploit the availability bilateral electrodes in other ways (see Quarterly Progress Report 4 for this project, for a detailed discussion of processing options for bilateral implants). This subject was referred to us by colleagues at the Julius-Maximilians Universität in Würzburg, and the studies with her were a cooperative effort between our two institutions. The subject was accompanied by Raymond Mederake of the Med El company in Starnberg, Germany, who also contributed to the studies.
- Studies with Ineraid subject SR1 during the two weeks beginning on June 5. The studies included measures of consonant identification and sentence recognition for CIS processors using a wide range of compression functions, (2) evaluation of processors with high rate "conditioner" pulses in addition to the pulses conveying information, (3) measures of consonant identification and monosyllabic word recognition for CIS processors using various rates of stimulation, and (4) measures of intracochlear evoked potentials for single pulses and for trains of unmodulated pulses, with pulse rates ranging from 100 to 2000/s.
- Studies with Ineraid subject SR8 during the week beginning on June 26. The studies included measures of complex tone perception, using CIS processors with different numbers of channels and with various selection criteria for complex tone partials within each channel. SR8 has a special ability to describe her percepts for complex tones, as she was a music major in college and continues to play and teach piano using hearing provided through her implant. The studies with her also included an initial evaluation of conditioner-pulses processors.
- A meeting among Bill Heetderks, Terry Hambrecht and Blake Wilson at NIH on May 4, to discuss progress and plans for the project.
- A visit by Marian Zerbi to RTI from May 6 to May 9, to assist with the development of software for simultaneous control of bilateral CI24M implants using the Cochlear Corporation's embedded protocol for those devices and to continue transferring her knowledge about the DSP and laboratory systems at RTI to Reinhold Schatzer.

- Presentation of project results in an invited talk by Wilson at the conference on *Binaural Hearing, Hearing Loss, and Hearing Aids*, held at the University of Iowa, June 22-24.
- Participation by Stefan Brill in the above conference.
- Completion of an Access database of processor designs and study results.
- 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 describe further studies to evaluate effects of changes in stimulus rate and envelope cutoff frequency for CIS processors. These studies extend those previously described in Quarterly Progress Report 6 for this project. Results from the other studies indicated in the list above will be presented in future reports.

II. Further studies to evaluate effects of changes in stimulus rate and envelope cutoff frequency for CIS processors

In Quarterly Progress Report 6 (QPR 6) for this project we described studies to evaluate effects of changes in stimulus rate and envelope cutoff frequency for CIS processors. The studies included (1) tests of consonant identification with a recorded male talker, for many combinations of rate and envelope cutoff frequency in 4- or 6-channel CIS processors, for each of four subjects; (2) tests of sentence recognition for seven combinations of rate and envelope cutoff frequency in a single-channel variation of CIS processors, for one subject; and (3) tests of consonant identification with male and female talkers, monosyllabic word recognition, and sentence recognition for various rates of stimulation while holding the envelope cutoff frequency constant, for each of four subjects. In broad terms, the results showed that large increases in speech reception performance can be obtained with increases in rate up to around 500 pulses/s/channel for multichannel processors, and with increases in envelope cutoff frequency up to 50 to 200 Hz using those same processors. Some subjects enjoyed further significant gains in performance with further increases in rate; indeed, with rare exception the highest scores were achieved by each subject at the highest rate used for each test. Results from the tests with the one subject using a single-channel processor indicated a significant advantage of an especially high rate (10162 pulses/s) compared with lower rates (833 and 2525 pulse/s). These latter results were obtained in the absence of electrode interactions, which may increase with increases in rate for multichannel processors.

In the present report we describe further studies involving manipulations in rate and envelope cutoff frequency in multichannel CIS processors, over wide ranges of both parameters. We have extended the prior studies by including additional tests in quiet for two of the subjects and by including tests in noise for another subject. The new studies include (1) tests of consonant identification for a recorded female talker, for two of the subjects previously tested with the male talker; (2) tests of sentence recognition for those same two subjects; and (3) tests of consonant identification in noise using the male talker, for another of the previously-tested subjects.

Methods

Many of the methods used for the prior studies also were applied for the present studies. In particular, the processors, stimulation equipment, test materials, and procedures for testing were the same across the two sets of studies. These methods are described in QPR 6.

Unlike the studies described in QPR 6, the present studies included presentation of consonants in competition with noise. CCITT noise was used, which has a spectrum that matches the long-term spectrum of speech.

Subjects SR2, SR9 and SR10 participated in the present studies. Characteristics of these subjects, such as levels of performance with their everyday speech processors, are presented in QPR 6.

Results

As noted above, the present studies included evaluation of possible talker effects in tests of consonant identification, measures of sentence recognition for the same processor conditions and subjects, and evaluation of effects of noise interference on consonant identification for a broad range of processor conditions.

Multiple talkers. Results from tests of consonant identification with male and female talkers are presented in Fig. 1, which shows interpolated contour plots of the percent correct scores for each subject and talker condition and for the two talkers combined. The percent correct scores underlying these plots, along with the standard error of the mean for each score, are presented in Appendix Fig. A.1.

The plots in Fig. 1 include contours over all possible combinations of rate and envelope cutoff frequency, for the indicated ranges of those parameters. However, combinations with cutoff frequencies above the rate of stimulation were not tested for subject SR9, and combinations with cutoff frequencies higher than one-half the rate of stimulation were not tested for subject SR10. Thus, the rightmost corner in each of the contour plots is extrapolated far beyond the data. Individual data points and their projections to the rate/cutoff frequency plane are provided to aid the reader in considering the contour shapes.

The ranges of tested rates and cutoff frequencies differed between the two subjects. Measurements with SR9 included rates from 50 to 2525 pulses/s/channel and cutoff frequencies from 12.5 to 1600 Hz, whereas the ranges for SR10 included rates from 100 to 1634 pulses/s/channel and cutoff frequencies from 50 to 800 Hz.

As described in QPR 6, the contour plots for the male talker convey an impression of decrements in percent correct scores with reductions in rate of stimulation, or envelope cutoff frequency, or both, below certain values. Also, both subjects appear to have a peak in scores at particular combinations of rate and cutoff frequency. Subject SR10, for instance, obtained his highest score for the male talker with the highest tested rate (1634 pulses/s/channel) and the cutoff frequency of 200 Hz.

The contour plots for the female talker resemble those for the male talker, for both subjects. Combinations of low rates and low cutoff frequencies produce decrements in performance, as is the case for the male talker. The highest scores for both subjects are obtained with the highest tested rate of stimulation and at intermediate cutoff frequencies.

Although the plots for the male and female talkers are broadly similar for both subjects, they are different in some ways as well. For subject SR9, scores with the female talker are lower than the scores with the male talker. Also, manipulations in rate and cutoff frequency do not appear to produce effects with the female talker that are as large as those observed with the male talker. For SR10, scores with the female talker are relatively uniform over a large portion of the parametric space, compared with the pattern of scores for the male talker. Scores obtained with the female talker generally approximate or exceed scores obtained with the male talker over the tested ranges of rates and cutoff frequencies for this subject.

The patterns for the combined talkers indicate (1) relatively high scores for the highest tested rates and intermediate cutoff frequencies for both subjects, and (2) decrements in performance with combinations of low rates and low cutoff frequencies.

Quantitative comparisons among the scores are presented in Fig. 2, which shows difference matrices for both subjects and for the male, female and combined talkers. Each matrix was derived by first calculating the mean of all percent correct scores for the selected subject and talker, and then subtracting the mean from each percent score in the percent correct matrix for that subject and talker (see Appendix Fig. A.1).

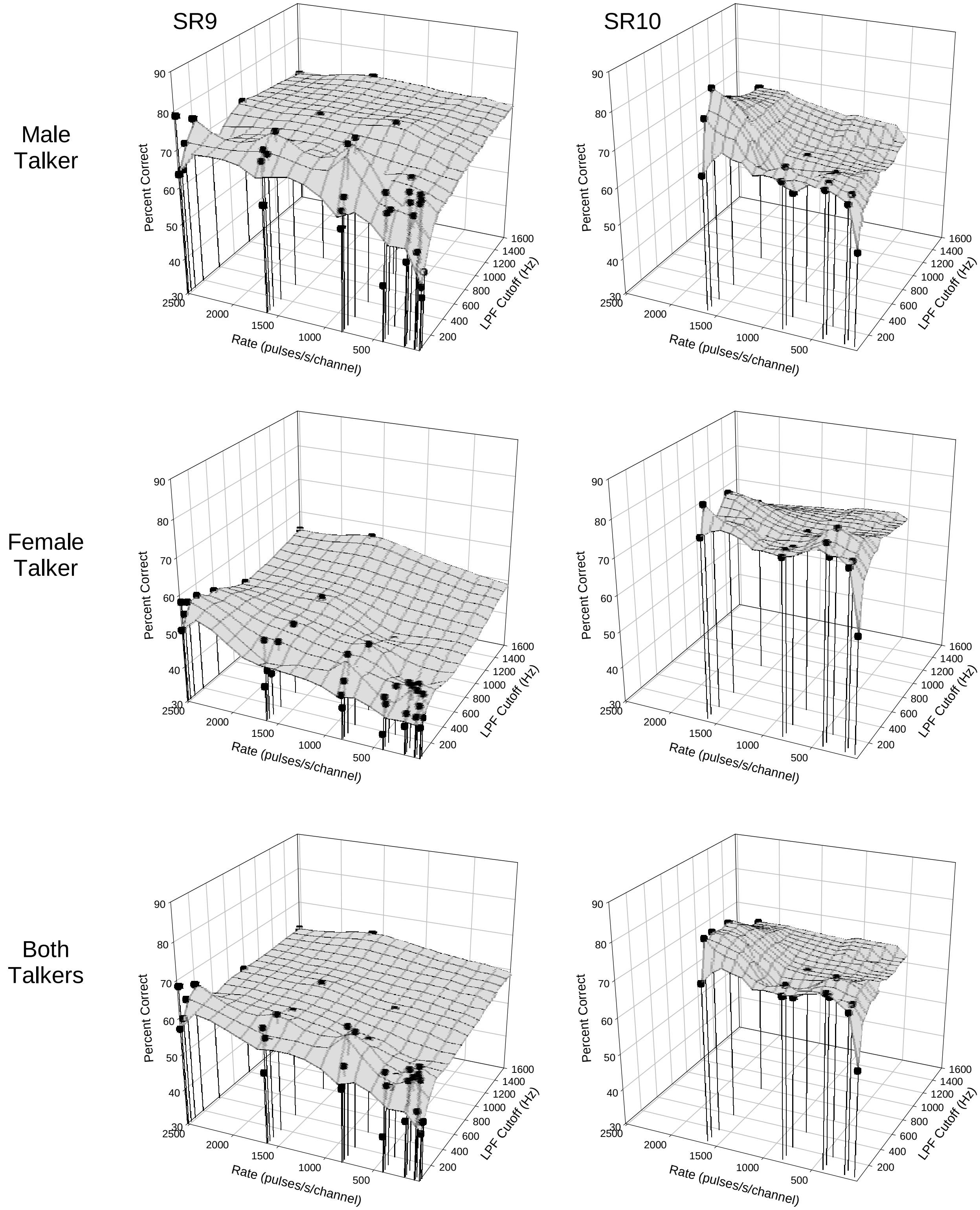

Fig. 1. Consonant identification for the male, female and combined talkers. Data for subject SR9 are from a 16 consonant test, and data for subject SR10 are from a 24 consonant test. Percent correct scores are shown as points; their projections to the rate/cutoff frequency plane and interpolated and extrapolated contour plots are provided as well. Matrices of the percent correct scores and associated standard errors of the means are presented in Appendix Fig. A.1. Note that the ranges of rates and envelope cutoff frequencies (LPF cutoff) are different between the two subjects.

Male Talker — SR9 (Rate (pulses/s/channel) × Lowpass Cutoff (Hz))

Rate	12.5	25	50	100	200	400	800	1600
50	-18.0	**-21.2**	-14.9					
100	-9.3	2.6	3.2	-11.2				
200	-12.4	5.1	2.0	-2.1	1.3			
417	**-19.9**	3.8	-1.7	-1.8	-4.3	1.3		
833	-7.4	-3.0	0.1	12.6	12.6	-1.8	7.6	
1634	-5.5	5.7	8.2	6.3	10.7	4.5	6.3	6.3
2525	-1.8	13.2	-1.2	5.1	10.1	-1.2	6.3	3.8

Male Talker — SR10

Rate	50	100	200	400	800
100	**-16.3**				
200	-4.6	-2.9			
417	-2.1	-1.3	-0.4		
833	-2.1	0.8	-7.5	-1.3	
1634	-4.6	9.2	**15.4**	10.0	7.5

Female Talker — SR9

Rate	12.5	25	50	100	200	400	800	1600
50	-7.5	1.2	-5.7					
100	-5.0	1.8	-2.9	-5.7				
200	-8.2	-5.0	2.8	0.9	-0.7			
417	-11.9	-1.9	-4.4	-7.2	-2.5	-9.4		
833	-3.8	-7.5	-0.7	5.6	-0.7	2.5	-3.8	
1634	-6.3	6.2	-2.5	-4.4	2.5	3.7	4.3	10.0
2525	4.3	11.8	8.1	10.6	10.6	8.7	4.3	8.1

Female Talker — SR10

Rate	50	100	200	400	800
100	**-17.2**				
200	-1.0	-0.1			
417	4.0	-0.1	5.3		
833	-1.4	-0.6	-1.4	-0.6	
1634	-0.1	7.4	1.5	6.1	-1.8

Both Talkers — SR9

Rate	12.5	25	50	100	200	400	800	1600
50	-12.8	-10.0	-10.3					
100	-7.2	2.2	0.2	-8.4				
200	-10.3	0.0	2.4	-0.6	0.3			
417	-15.9	1.0	-3.1	-4.5	-3.4	-4.0		
833	-5.6	-5.3	-0.3	9.1	6.0	0.3	1.9	
1634	-5.9	6.0	2.8	1.0	6.6	4.1	5.3	8.1
2525	1.3	12.5	3.5	7.8	10.3	3.8	5.3	6.0

Both Talkers — SR10

Rate	50	100	200	400	800
100	**-16.7**				
200	-2.8	-1.5			
417	1.0	-0.7	2.4		
833	-1.7	0.1	-4.4	-0.9	
1634	-2.4	8.3	8.5	8.1	2.8

Rate (pulses/s/channel); Lowpass Cutoff (Hz)

Fig. 2. Difference matrices for tests of consonant identification with the male and female talkers and with both combined, subjects SR9 and SR10. (Please see full caption on the next page.)

Fig. 2. Difference matrices for tests of consonant identification with the male and female talkers and with both combined, subjects SR9 and SR10. Each matrix was derived by subtracting the mean of all percent-correct scores for that matrix (see Appendix Fig. A.1) from the percent-correct score in each cell. A one-way analysis of the variance (ANOVA) was conducted to evaluate the possibility of significant differences among the scores for each matrix. The ANOVAs indicated significant differences for all six matrices in this figure (and the corresponding matrices in Fig. A.1). Shaded areas in each matrix above indicate scores that are significantly different from the mean according to the Fisher least-significant-difference (LSD) criterion ($p < 0.05$), and the bold type indicates scores that are significantly different from the mean according to the more-conservative Tukey honestly-significant-difference (HSD) criterion ($p < 0.05$). Light shading indicates scores significantly below the mean, and dark shading indicates scores significantly above the mean. Underlines indicate the minimum and maximum values in each matrix. Scores within the heavy lines (for subject SR9) were obtained with 20 blocks of the consonant tests for the male and female talkers, and with 40 blocks for the combined talkers. Scores outside the lines for SR9, and all scores for SR10, were obtained with 10 blocks each for the male and female talkers, and with 20 blocks for the combined talkers.

A one-way analysis of the variance (ANOVA) was conducted for each of the matrices in Fig. 2 and in each case indicated significant differences among the difference scores (or the raw scores, which would produce the same result in a one-way ANOVA). The shaded areas in each matrix identify processor conditions that produced scores that are significantly different from the grand mean of all scores according to the *post-hoc* Fisher least-significant-difference (Fisher LSD) criterion ($p < 0.05$), and the bold type identifies conditions that produced scores that are significantly different from the mean according to the Tukey honestly-significant-difference (Tukey HSD) criterion ($p < 0.05$). The light shading indicates scores significantly below the mean, and the dark shading indicates scores significantly above the mean. The underlined type indicates the maximum and minimum values in each matrix. Note that the Tukey HSD criterion is more conservative than the Fisher LSD criterion (*i.e.*, a greater number of scores are identified as significantly different from the mean using the Fisher LSD criterion).

In all but one of the matrices, scores that are significantly below the mean are restricted to the lowest tested rate, the lowest tested cutoff frequency, or both. In the matrix for subject SR9 and the male talker, a score significantly below the mean also is found at the relatively low rate of 100 pulses/s/channel and the cutoff frequency of 100 Hz. Conversely, scores that are significantly above the mean are obtained with either relatively high rates (male talker, subject SR9) or the highest tested rate (all other matrices), combined with intermediate cutoff frequencies.

The Fisher LSD and Tukey HSD for *post hoc* comparisons in each matrix of Fig. 2 are presented in Table 1. These values allow comparisons of scores between any two cells within one of the matrices. Differences in scores that exceed the Fisher LSD are significant according to that criterion, and differences that exceed the Tukey HSD are significant according to that more-conservative criterion.

Another view of the results is presented in Figs. 3 and 4. These figures show slices through the rate/cutoff frequency data for each of the subjects, respectively. The left column in each figure shows slices along rows in the matrices of the percent correct scores (Fig. A.1), and the right column in each figure shows slices along columns in the matrices. Plots in the left columns of the figures thus indicate the dependence of scores on the cutoff frequency, with rate of stimulation as

Table 1. Critical values for comparisons between scores within matrices in Figs. 2 and A.1.

		Fisher LSD			Tukey HSD		
Subject	Talker(s)	outside[a]	across[b]	within[c]	outside[a]	across[b]	within[c]
SR9	Male	9.85	8.53	6.97	19.69	17.05	13.92
	Female	10.74	9.30	7.59	21.46	18.59	15.18
	Both	9.66	8.37	6.38	19.26	16.68	13.62
SR10	Male	8.06			14.08		
	Female	6.49			11.33		
	Both	5.79			10.06		

[a]Comparison between cells outside the heavy lines in a matrix
[b]Comparison between a cell outside and a cell within the heavy lines in a matrix
[c]Comparison between cells within the heavy lines in a matrix

the parameter, and the right columns indicate the dependence of scores on the rate of stimulation, with cutoff frequency as the parameter. Standard errors of the means for the scores presented in Figs. 3 and 4 can be found in Fig. A.1. The standard errors ranged from 1.3 to 4.9 percent for subject SR9, and from 1.3 to 4.0 percent for subject SR10.

Additional data collected in tests with SR10 using the male talker are shown for reference by the gray symbols and lines in Fig. 4. These are the data that were reported in QPR 6 for this subject and talker. (The range of cutoff frequencies covered for the female talker is smaller than that covered for the male talker for this subject.)

The plots in Fig. 3 appear to show a general increase in scores with increases in cutoff frequency or rate. Scores for the cutoff frequency of 12.5 Hz, for instance, appear to be lower than the scores for higher cutoff frequencies, at least for the male talker. Scores appear to increase over the range of tested rates for the male talker, with the largest increase at the increment in rate from 50 to 100 pulses/s/channel. Scores for the female talker appear to increase with increases in rate beyond 417 or 833 pulses/s/channel. Scores for the combined talkers appear to increase over the tested range of rates.

The plots in Fig. 4 do not seem to show a sensitivity to changes in cutoff frequency for the fixed rates above 100 pulses/s/channel and over the range of cutoffs tested with both talkers (from 50 to 800 Hz). With the inclusion of the additional data for the male talker, scores appear to rise with increases in cutoff frequency from 12.5 to 50 Hz. In that case, increases in rate (right column) also appear to produce increases in scores, at least from 100 to 200 pulses/s/channel and the cutoff frequency conditions common to both talkers. Inclusion of the additional data for the male talker appears to diminish the effect of increases in scores with increases in rate.

Overall effects of changes in cutoff frequency and rate of stimulation are illustrated in Fig. 5 for subject SR9 and in Fig. 6 for subject SR10. The plots in the left columns of these figures show the average of scores for all tested rates of stimulation at and above 200 pulses/s/channel (scores from the left columns of Figs. 3 and 4 versus cutoff frequency), and the plots in the right column show the average of scores for all tested cutoff frequencies at and above 25 Hz (scores from the right columns of Figs. 3 and 4 versus rate of stimulation). Lower rates and lower cutoffs were excluded in the derivation of plots for the left and right columns, respectively, because these

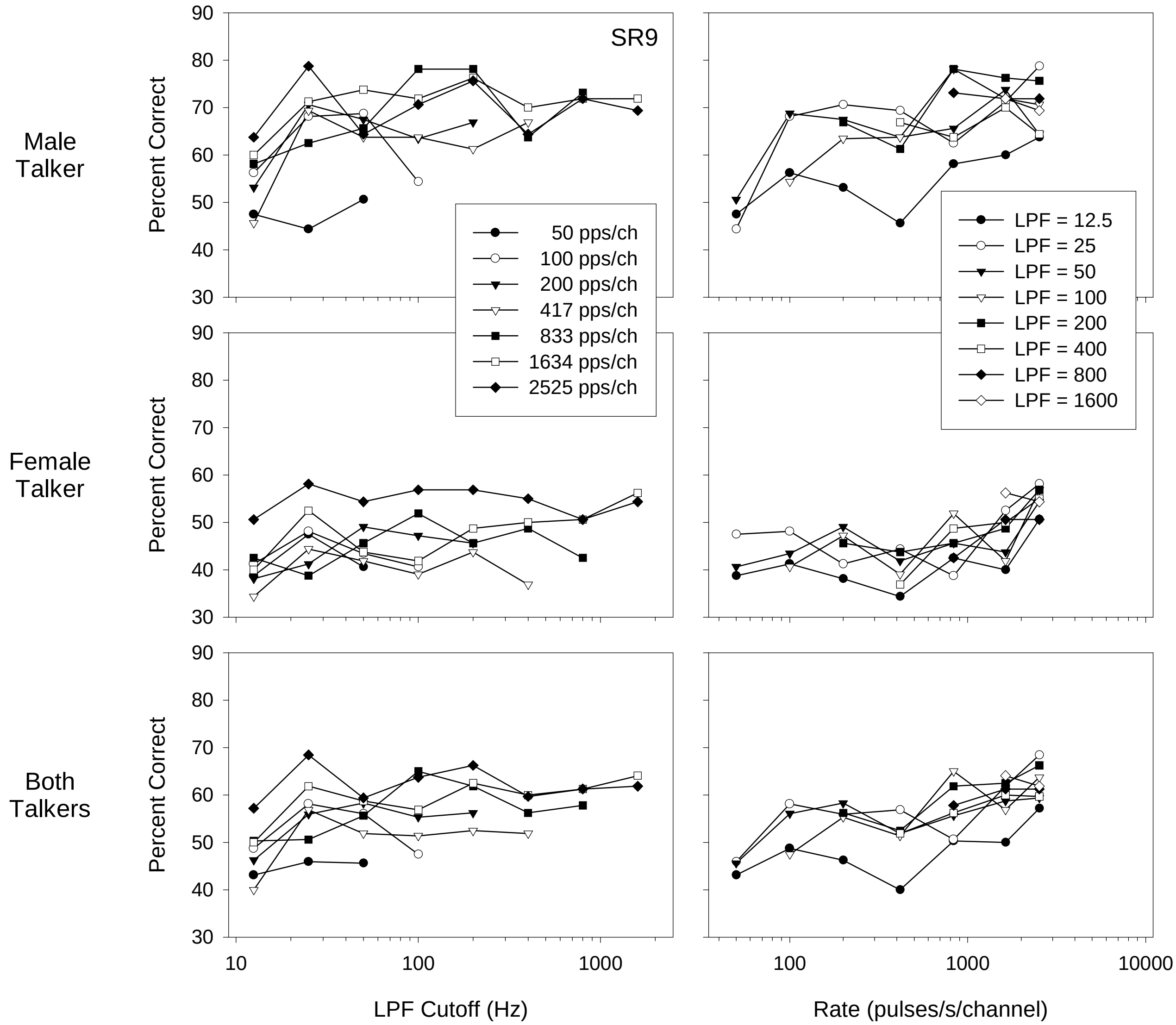

Fig. 3. Slices through the rate/cutoff frequency data for subject SR9, from tests of consonant identification with male and female talkers and with both combined. The left column shows slices along rows in the matrices of the percent correct scores for this subject (Fig. A.1), and the right column shows slices along columns in the matrices. Plots in the left column indicate the dependence of scores on cutoff frequency while holding the rate of stimulation constant, whereas plots in the right column indicate the dependence of scores on rate of stimulation while holding the cutoff frequency constant. Standard errors of the means for the scores ranged from 1.3 to 4.9 percent and are presented in Fig. A.1. The legend for the left column indicates rates of stimulation in pulses/s/channel (pps/ch), and the legend in the right column indicates envelope cutoff frequencies in Hz (LPF).

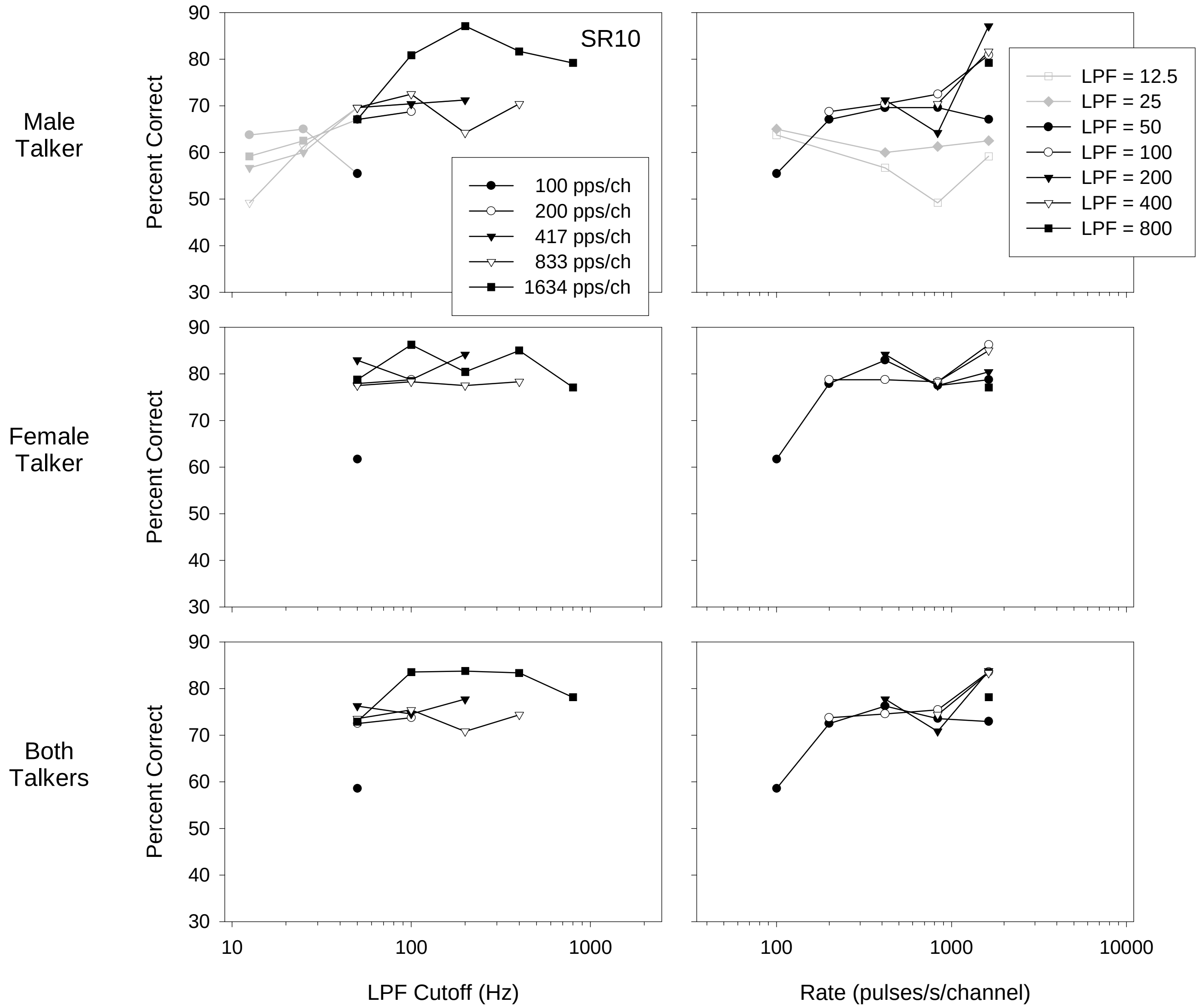

Fig. 4. Slices through the rate/cutoff frequency data for subject SR10, from tests of consonant identification with male and female talkers and with both combined. As in Fig. 3, the left column shows slices along rows in the matrices of the percent correct scores for this subject (Fig. A.1), and the right column shows slices along columns in the matrices. Standard errors of the means for the scores ranged from 1.3 to 4.0 percent and are presented in Fig. A.1. The gray symbols and lines show scores for additional conditions tested with the male talker for this subject.

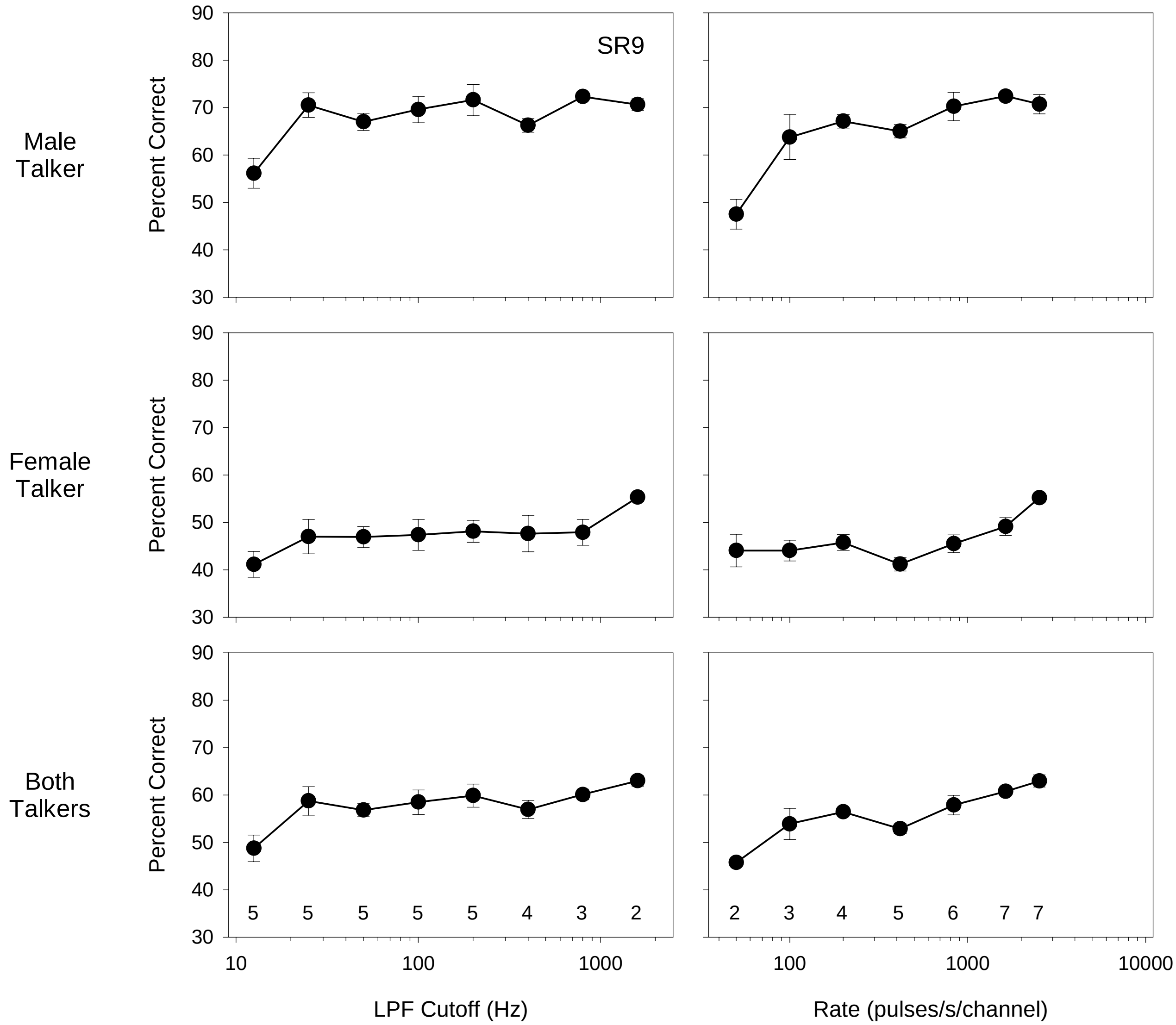

Fig. 5. Averages of scores derived from data in corresponding panels of Fig. 3, for subject SR9. The plots in the left column of the present figure show the averages of scores for all tested rates of stimulation at and above 200 pulses/s/channel, and the plots in the right column show the averages of scores for all tested cutoff frequencies at and above 25 Hz. The numbers in the bottom panels for each column indicate the number of scores included in calculations of the means for each cutoff frequency (left column) or each rate (right column). The bars show standard errors of the means.

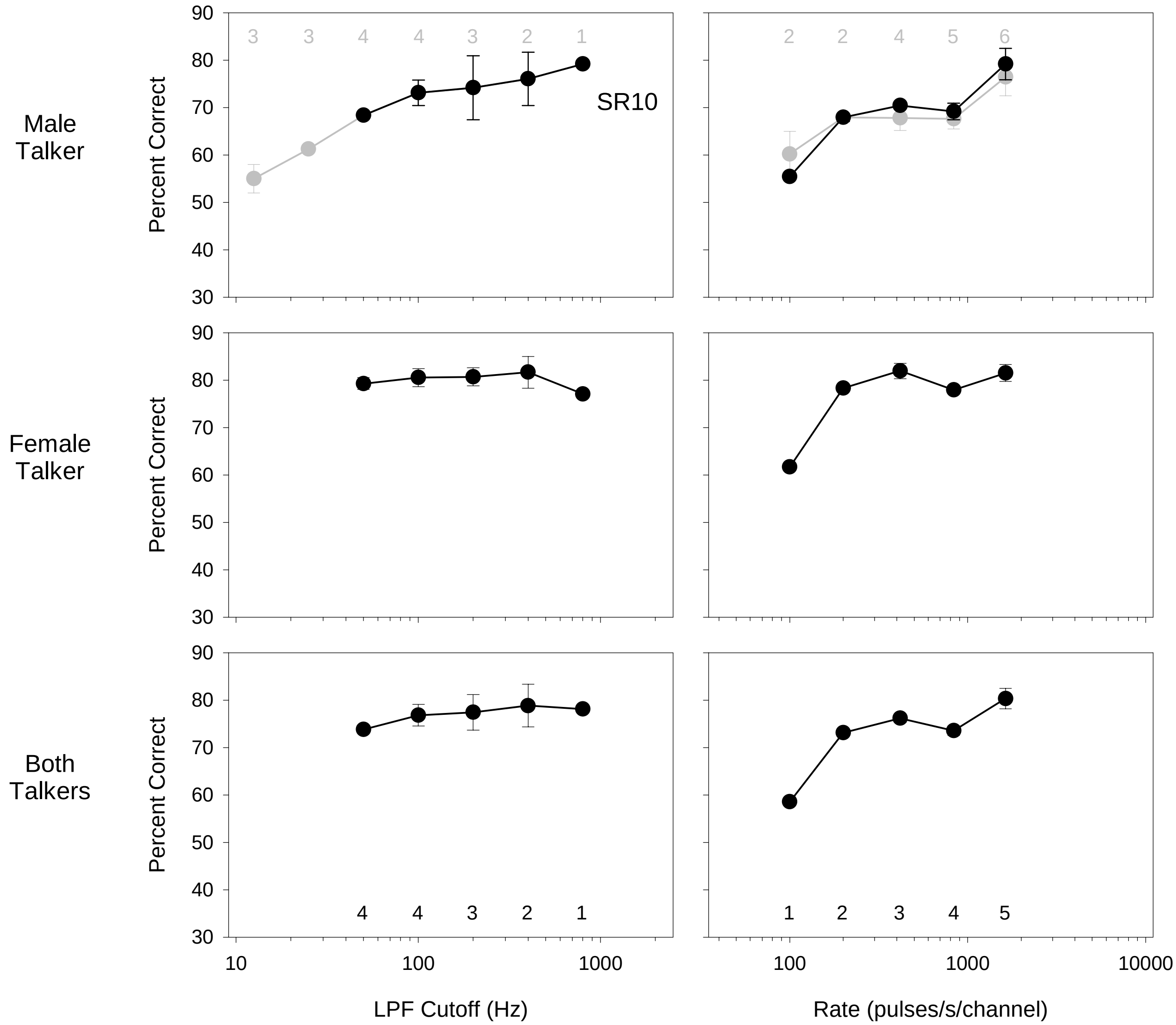

Fig. 6. Averages of scores derived from data in corresponding panels of Fig. 4, for subject SR10. As in Fig. 5, plots in the left column of the present figure show the averages of scores for all tested rates of stimulation at and above 200 pulses/s/channel, and the plots in the right column show the averages of scores for all tested cutoff frequencies at and above 25 Hz. The numbers in the bottom panels for each column indicate the number of scores included in calculations of the means for each cutoff frequency (left column) or each rate (right column). The bars show standard errors of the means. The gray symbols and lines show results with the inclusion of additional data collected for this subject in tests with the male talker (see Fig. 4). The gray numbers in the top panels indicate the number of scores included in the calculations of the means with the additional data.

conditions produced clearly lower and sometimes different patterns of scores compared to the included conditions. (This procedure also was followed in the derivation of similar figures for QPR 6.) The numbers in the bottom panels indicate how many scores were included in the calculations of the average values. The error bars show standard errors of the means. The gray symbols and lines in Fig. 6 show results from inclusion of the additional cutoff frequency conditions used in the prior tests with subject SR10.

A one-way ANOVA was conducted for the data in each of the panels in Figs. 5 and 6. The results are presented in Table 2 for subject SR9 (corresponding to Fig. 5) and in Table 3 for subject SR10 (corresponding to Fig. 6).

The ANOVAs and *post hoc* tests indicate a significant increase in scores for the male and combined talkers for SR9, with an increase in the cutoff frequency from 12.5 to 25 Hz (see left column of Fig. 5). Further increases in cutoff frequency do not produce further significant increases in scores. The ANOVA for the female talker is not significant, indicating that manipulations in cutoff frequency over the tested range do not affect scores with that talker for this subject.

The ANOVAs and *post hoc* tests indicate significant increases in scores for each of the talker conditions for SR9 with increases in rate (see right column of Fig. 5). The highest scores are obtained at or near the highest tested rate for either of the talkers. The largest increases in scores for the male talker are produced with the increase in rate from 50 to 100 pulses/s/channel and from 417 to 1634 pulses/s/channel, whereas the largest increases in scores for the female talker are produced with increases in rate from 417 to 2525 pulses/s/channel. The score at 2525 pulses/s/channel is significantly higher than the score at 1634 pulses/s/channel. Increases in scores for the combined talkers are obtained with an increase in rate from 50 pulses/s/channel to any of the intermediate rates between 100 and 417 pulses/s/channel and from that range of rates to the higher tested rates.

For SR10, none of the ANOVAs for manipulations in cutoff frequency is significant, at least for the range of cutoffs included for all talker conditions (see left column of Fig. 6). This indicates that changes in cutoff between 50 and 800 Hz did not affect scores. However, inclusion of data for lower cutoffs does produce a significant ANOVA for the male talker ($p < 0.01$; see additional gray symbols and lines in the top left panel of Fig. 6). *Post hoc* tests for that case indicate that scores for cutoffs at and above 100 Hz are significantly higher than the scores for the cutoffs of 12.5 and 25 Hz, and that the score for the 50 Hz cutoff is higher than the score for the 12.5 Hz cutoff, as previously reported in QPR 6.

The ANOVAs for manipulations in rate indicate significant differences among scores for the male and combined talkers, but not for the female talker, for the range of rates common to all talker conditions. For the male talker, the score at the highest tested rate of 1634 pulses/s/channel is significantly higher than the scores at all lower rates, and the scores at 833 and 417 pulses/s/channel are significantly higher than the score at 100 pulses/s/channel. For the combined talkers, the score at 1634 pulses/s/channel is significantly higher than the scores at 833, 200 and 100 pulses/s/channel (but not at 417 pulses/s/channel), and the scores at 833, 417 and 200 pulses/s/channel are significantly higher than the score at 100 pulses/s/channel.

The pattern of scores for the female talker in the right column of Fig. 6 is similar to the patterns for the male and combined talker conditions. However, the ANOVA for the female talker is not significant, whereas the ANOVAs for the other conditions are significant. A possible contributor to this seemingly curious result is that only one point is included in the "average" of scores for the

Table 2. Significant differences among scores for the cutoff frequency and rate of stimulation conditions presented in Fig. 5 (data for subject SR9). The differences indicated are those identified by the Fisher LSD criterion ($p < 0.05$). Entries for cutoff frequencies are in Hz, and entries for rate of stimulation are in pulses/s/channel.

Talker(s)	Manipulation	ANOVA	Significant Differences
Male	Cutoff frequency	$p < 0.005$	1600, 800, 400, 200, 100, 50, 25 > 12.5
Female		NS	
Both		$p < 0.05$	1600, 800, 400, 200, 100, 50, 25 > 12.5
Male	Rate	$p < 0.001$	1634 > 417, 100, 50
			2525, 833, 417, 200, 100 > 50
Female		$p < 0.001$	2525 > 1634, 833, 417, 200, 100, 50
			1634 > 417
Both		$p < 0.001$	2525 > 833, 417, 200, 100, 50
			1634 > 417, 100, 50
			833 > 417, 50
			417, 200, 100 > 50

Table 3. Significant differences among scores for the cutoff frequency and rate of stimulation conditions presented in Fig. 6 (data for subject SR10). The differences indicated are those identified by the Fisher LSD criterion ($p < 0.05$). Entries for cutoff frequencies are in Hz, and entries for rate of stimulation are in pulses/s/channel.

Talker(s)	Manipulation	ANOVA	Significant Differences
Male	Cutoff frequency	NS	
Female		NS	
Both		NS	
Male	Rate	$p < 0.05$	1634 > 833, 417, 200, 100
			833, 417 > 100
Female		NS	
Both		$p < 0.05$	1634 > 833, 200, 100
			833, 417, 200 > 100

lowest rate of 100 pulses/s/channel. Thus, the apparently-large decrement in the score at that rate contributes little to the ANOVA, which includes the average scores at each of the higher rates, all computed with higher numbers of scores. For the ANOVA to be significant, there must either be an even larger difference between the score at 100 pulses/s/channel and the scores at all other rates, or there must be large differences among scores at those other (higher) rates. The data for subject SR10 show the latter differences for the male talker and combined talkers, but not for the female talker.

Inclusion of all data for the male talker reduces slightly the differences among scores across rates for SR10 (see gray symbols and lines in the top right panel of Fig. 6). The ANOVA for all data just fails to attain significance ($p = 0.083$).

CUNY sentences. Results from the tests of sentence recognition are presented in Fig. 7, which shows interpolated and extrapolated contour plots of the percent correct scores for subjects SR9 and SR10. The percent correct scores underlying these plots, along with the standard errors of the means for the scores, are presented in Appendix Fig. A.2. Four separate lists of the CUNY sentences were used in the measures for each processor with each subject. The lists were not repeated within or across conditions for either of the subjects.

The plots in Fig. 7 show contours over all possible combinations of rate and cutoff frequency, for the indicated ranges of those parameters. However, combinations with cutoff frequencies higher than one-half the rate of stimulation were not tested with either subject. Individual points and their projections to the rate/cutoff frequency plane are provided to indicate where the contours represent interpolation or extrapolation of the data.

Quantitative comparisons among the scores are presented in Fig. 8, which shows difference matrices for the two subjects. A one-way ANOVA was conducted for each matrix and was significant for subject SR9 but not for subject SR10.

The results from the CUNY tests are similar to the results from the consonant tests for subject SR9. The shape of the contour plot for CUNY sentences (left column of Fig. 7) approximates the shapes of the plots for consonant identification for each of the talker conditions (three plots in the left column of Fig. 1; note that the ranges of rates and cutoff frequencies are both greater in these plots for consonant identification than in the plot for the CUNY sentences). The maximum scores for both the CUNY and consonant tests are obtained with the highest tested rate of stimulation and either an intermediate or the highest tested cutoff frequency. The minimum scores are obtained at the lowest tested cutoff frequency or at the lowest tested rate or both.

For SR10, the contour plot for the CUNY sentences is much flatter than the plots for consonant identification. Indeed, the ANOVA for the CUNY scores is not significant.

In broad terms, results from tests with the CUNY sentences reflect results from tests of consonant identification for subject SR9. The tests with the CUNY sentences appear to be as sensitive, or perhaps somewhat more sensitive, as the consonant tests in demonstrating effects of rate and cutoff frequency manipulations for this subject. In contrast, the CUNY tests are not as sensitive as the consonant tests in demonstrating such effects for subject SR10. Note, however, that range of CUNY scores is quite different between the subjects. Scores for SR9 range from 29 to 68 percent correct, whereas scores for SR10 range from 80 to 98 percent correct. Most of the scores for SR10 are 90 percent correct or higher. Thus, ceiling effects may well have diminished the sensitivity of the CUNY tests for that subject.

Consonants presented in competition with noise. Effects of noise interference were evaluated in tests of consonant identification with subject SR2. The conditions included especially wide ranges of processor parameters and consonants presented in quiet and at the speech-to-noise ratios of +10 and +5 dB. As noted before, CCITT noise was used, which has a spectrum that approximates the long-term spectrum of speech.

The principal results are presented in Figs. 9 and 10, which show contour plots and difference matrices, respectively, for the quiet and +10 and +5 dB speech-to-noise conditions. The percent

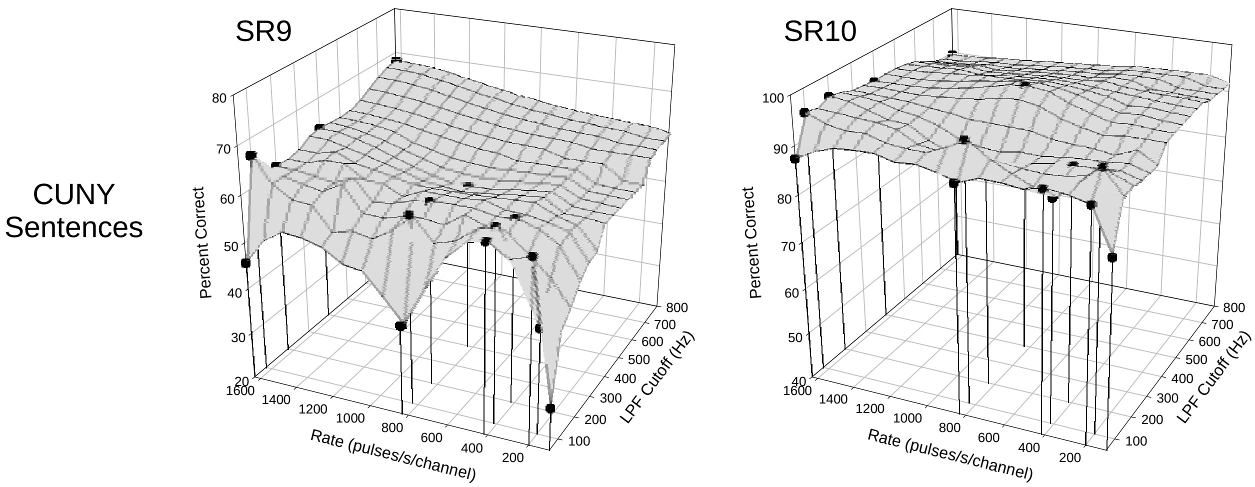

Fig. 7. Recognition of CUNY sentences by subjects SR9 and SR10, male talker. Percent correct scores are shown as points; their projections to the rate/cutoff frequency plane and interpolated and extrapolated contour plots are provided as well. Matrices of the percent correct scores and associated standard errors of the means are presented in Appendix Fig. A.2. Note that the ranges for the rate and cutoff frequency (LPF Cutoff) axes in this figure are different from those in Fig. 1.

correct scores used to derive these figures are presented in Appendix Fig. A.3. Figure A.3 also shows the standard errors of the means for the scores.

As noted in the caption to Fig. 10, some of the scores for the +10 dB speech-to-noise ratio (S/N) were obtained under questionable conditions. The score marked with a superscripted "a" in Fig. 10 was obtained with a processor whose implementation may have been flawed (and was identified at the time as a processor that needed to be checked and tested again). The scores marked with a superscripted "b" in Fig. 10 were obtained during a common period when the subject volunteered that he was experiencing especially severe tinnitus, which may have affected his performance in the tests.

Given the questions associated with some of the scores for the +10 dB conditions, a separate contour plot and a separate difference matrix were derived from a subset of the collected data with the questionable points removed. The additional contour plot is shown in the right column of Fig. 9, and the additional difference matrix is shown in the right column of Fig. 10. The corresponding plot and matrix in the left columns of Figs. 9 and 10 were derived from all of the collected data.

A one-way ANOVA was conducted for each of the matrices in Fig. 10 and in each case indicated significant differences among the scores. Results from *post hoc* tests using the Fisher LSD and Tukey HSD criteria are indicated by shading and boldface type, as described in the caption to Fig. 2. Underlines identify the maximum and minimum scores in each matrix. Critical values for comparisons using either the Fisher LSD or Tukey HSD are presented in Table 4.

CUNY Sentences

SR9

Rate (pulses/s/channel)	50	100	200	400	800
100	**<u>-26.4</u>**				
200	3.5	-12.7			
417	4.7	5.9	4.0		
833	-16.1	4.9	4.3	0.8	
1634	-9.8	11.1	5.7	7.9	<u>12.5</u>

Lowpass Cutoff (Hz)

SR10

Rate (pulses/s/channel)	50	100	200	400	800
100	-10.8				
200	-1.7	3.7			
417	-0.3	-3.7	-0.7		
833	-2.2	4.4	-4.4	6.8	
1634	-3.2	4.6	5.1	2.9	-1.2

Lowpass Cutoff (Hz)

Fig. 8. Difference matrices for recognition of CUNY sentences, male talker, subjects SR9 and SR10. Each matrix was derived by subtracting the mean of all percent correct-scores for that matrix (see Appendix Fig. A.2) from the percent-correct score in each cell. A one-way analysis of the variance (ANOVA) was conducted to evaluate the possibility of significant differences among the scores for each matrix. The ANOVA was significant for SR9 but not for SR10. Shaded areas in the matrix for SR9 indicate scores that are significantly different from the mean according to the Fisher LSD criterion ($p < 0.05$; Fisher LSD = 12.9), and the bold type indicates the one score that is significantly different from the mean according to the Tukey HSD criterion ($p < 0.05$; Tukey HSD = 23.04). For this matrix all scores significantly different from the mean are below the mean. Underlines indicate the maximum and minimum values in the matrix for SR9.

As described in QPR 6, results for the consonants presented in quiet show decrements in performance with low rates and low cutoff frequencies. Conversely, scores that are significantly above the mean of all scores are obtained with relatively high rates and relatively high cutoff frequencies. The very lowest scores are obtained with rates at and below 125 pulses/s/channel and cutoff frequencies at and below 50 Hz. The highest score is obtained at the highest tested rate (6900 pulses/s/channel) and at a relatively high cutoff frequency (500 Hz).

The pattern of scores for consonants presented in competition with noise at the S/N of +10 dB is somewhat similar to the pattern for consonants presented in quiet. The lowest scores are again obtained with low rates and cutoff frequencies, and the highest scores are again obtained with combinations of relatively high rates and relatively high cutoff frequencies. The minimum score for consonants in quiet is at the rate of 50 pulses/s/channel and the cutoff frequency of 25 Hz, and the minimum score for consonants presented in noise at the +10 dB S/N is at that rate and the nearby cutoff frequency of 50 Hz. Similarly, the maximum score for consonants in quiet is at the rate of 6900 pulses/s/channel and the cutoff frequency of 500 Hz, and the maximum score for consonants presented in noise at the +10 dB S/N is at that rate and the nearby cutoff frequency of 250 Hz.

A difference in the patterns of scores for consonants presented in quiet versus consonants presented in noise at the +10 dB S/N is that the dependence on both rate and cutoff frequency appears to be more gradual for the consonants presented in noise. The contour plots for the +10 dB conditions show a more-or-less continuous reduction in scores with reductions in rate across the tested range, and a more-or-lees continuous reduction in scores with reductions in cutoff

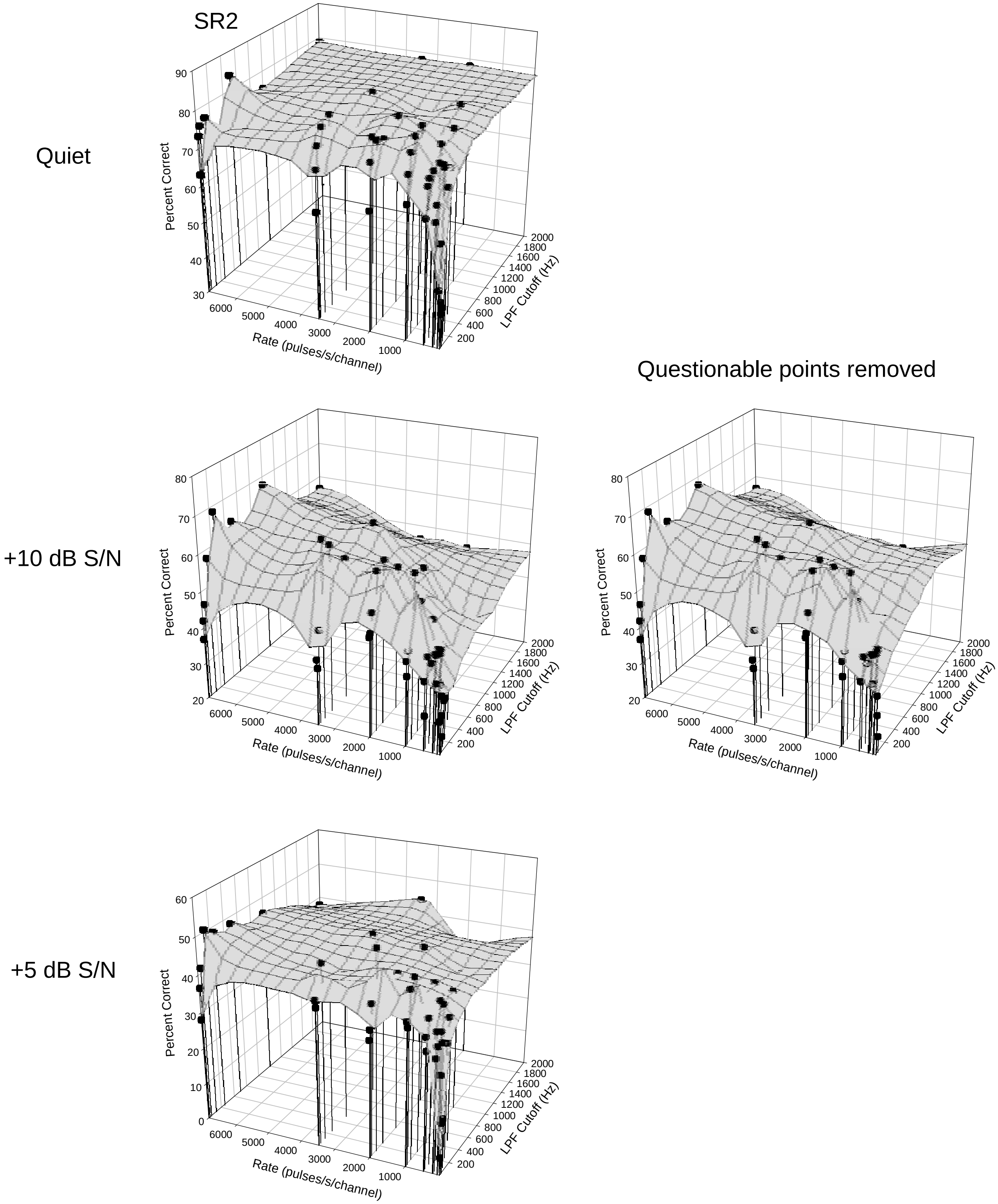

Fig. 9. Consonant identification with the male talker in quiet and in competition with speech-spectrum noise at the speech-to-noise ratios of +10 and +5 dB, subject SR2. Percent correct scores are shown as points; their projections to the rate/cutoff frequency plane and interpolated and extrapolated contour plots are provided as well. Matrices of the percent correct scores and associated standard errors of the means are presented in Appendix Fig. A.3. Some of the scores for the speech-to-noise ratio of +10 dB are for tests conducted under questionable conditions: a possible flaw in the implementation of one processor and exceptionally strong tinnitus during the testing of several others. These questionable scores are identified in Fig. 10. The right panel in the present figure shows a contour plot derived from the scores that remained after all questionable scores were removed.

SR2

Quiet

Rate (pulses/s/channel)	12.5	25	50	125	250	500	1000	2000
50	**-28.9**	**-32.2**	**-31.0**					
125	**-26.0**	-13.4	4.9	-1.0				
250	-8.5	-4.3	5.7	4.4	1.9			
500	-8.1	-0.1	1.5	2.4	7.4	8.2		
1000	-5.4	1.9	6.9	9.9	11.1	3.2	7.8	
2000	-8.9	3.2	9.0	7.4	6.1	9.0	2.4	6.5
3500	-12.2	-1.4	4.4	8.2	9.9	1.9	7.4	6.3
6900	-8.5	1.5	4.0	5.3	-2.2	12.4	3.6	6.9

+10 dB S/N

Rate (pulses/s/channel)	12.5	25	50	125	250	500	1000	2000
50	-10.9	**-16.3**	**-22.6**					
125	-0.1	0.8	b **-18.8**	b -14.2				
250	-0.5	-0.9	-8.8	b -10.5	b **-15.9**			
500	-8.0	a **-17.6**	-2.1	-5.1	-3.4	b -9.2		
1000	-3.8	-8.0	-1.7	**17.0**	8.3	-0.1	b -11.7	
2000	0.4	1.2	6.2	15.8	**17.0**	12.0	5.4	-1.3
3500	-8.8	-11.3	-1.3	**21.2**	**18.3**	11.6	15.4	-0.9
6900	-10.1	-5.1	-0.9	10.8	**21.6**	**16.2**	**20.8**	9.5

Questionable points removed

Rate (pulses/s/channel)	12.5	25	50	125	250	500	1000	2000
50	-13.2	**-18.6**	**-24.9**					
125	-2.4	-1.5						
250	-2.8	-3.2	-11.1					
500	-10.3		-4.5	-7.4	-5.7			
1000	-6.1	-10.3	-4.0	14.7	5.9	-2.4		
2000	-2.0	-1.1	3.9	13.5	14.7	9.7	3.0	-3.6
3500	-11.1	-13.6	-3.6	**18.9**	**16.0**	9.3	13.0	-3.2
6900	-12.4	-7.4	-3.2	8.5	**19.3**	13.9	**18.5**	7.2

Lowpass Cutoff (Hz)

+5 dB S/N

Rate (pulses/s/channel)	12.5	25	50	125	250	500	1000	2000
50	**-32.9**	**-23.7**	**-22.9**					
125	0.0	-11.2	-3.3	-4.6				
250	-7.1	-0.4	-4.6	5.0	0.0			
500	-2.1	-5.8	2.1	-9.6	3.8	2.9		
1000	0.9	-0.8	8.4	10.4	4.6	4.2	0.4	
2000	-5.8	-3.3	2.9	15.9	4.6	5.0	5.9	-5.4
3500	1.7	-0.4	1.3	9.6	3.4	2.1	7.1	6.3
6900	-9.6	-1.2	3.8	12.9	10.9	10.4	7.9	0.0

Lowpass Cutoff (Hz)

Fig. 10. (Please see caption on the next page.)

Fig. 10. Difference matrices for tests of consonant identification in quiet and in competition with speech-spectrum noise at the speech-to-noise ratios of +10 and +5 dB, male talker, subject SR2. Each matrix was derived by subtracting the mean of all percent correct-scores for that matrix (see Appendix Fig. A.3) from the percent-correct score in each cell. A one-way analysis of the variance (ANOVA) was conducted to evaluate the possibility of significant differences among the scores for each matrix. The ANOVAs indicated significant differences for all matrices in the figure. Some of the scores for the speech-to-noise ratio of +10 dB are for tests conducted under questionable conditions: a possible flaw in the implementation of one processor (corresponding to the cell marked with a superscripted "a" in the middle matrix in the left column) and exceptionally strong tinnitus during the testing of several others (corresponding to the cells marked with a superscripted "b"). A difference matrix computed from the scores that remained after the questionable scores were removed is presented in the right column. The meanings of shadings, bold type, underlined type, and heavy lines around cells are presented in the caption to Fig. 2.

Table 4. Critical values for comparisons between scores within matrices in Figs. 10 and A.3.

	Fisher LSD			Tukey HSD		
Noise Condition	outside[a]	across[b]	within[c]	outside[a]	across[b]	within[c]
Quiet	6.81	5.89	4.81	13.89	12.03	9.82
+10 dB S/N, all points	7.77			15.86		
+10 dB S/N, questionable points removed	7.65			15.35		
+5 dB S/N	8.02	7.32		16.38	14.95	

[a]Comparison between cells outside the heavy lines in a matrix
[b]Comparison between a cell outside and a cell within the heavy lines in a matrix
[c]Comparison between cells within the heavy lines in a matrix

frequency from 100 Hz to the lowest tested value of 12.5 Hz. In contrast, the plot for consonants presented in quiet shows a more precipitous decrement in performance with combinations of very low rates and low cutoff frequencies, and a smaller region of relatively high scores with combinations of the highest tested rate and intermediate cutoff frequencies.

Comparison of the left and right columns in Figs. 9 and 10 shows that the overall pattern of results for the +10 dB S/N is not affected by removal of the questionable points. Indeed, only subtle differences can be found between the two contour plots presented in Fig. 9 for the +10 dB S/N. (We note that the data points we have identified as having been obtained under questionable conditions may, in fact, reflect a significant additional feature in the performance contour. We plan to revisit those parameter combinations at the next opportunity with the same subject.)

The pattern of scores for consonants presented at the +5 dB S/N is similar to the pattern for consonants presented in quiet. Both patterns show precipitous decrements in performance with combinations of low rates and low cutoff frequencies, and both patterns show better than average performance with relatively high rates and relatively high cutoff frequencies. The patterns for quiet and +5 dB S/N also show broad regions of relatively uniform scores, in contrast to the pattern observed for the +10 dB S/N.

Not surprisingly, the addition of competing noise reduces the mean of all scores for the various processor conditions. The mean of all scores for consonants presented in quiet is 71.8 percent correct, whereas the means for the +10 and +5 dB noise levels are 47.1 and 37.9 percent correct, respectively. (The mean for the +10 dB level with the questionable points removed is 49.5 percent correct.)

Slices through the rate/cutoff frequency data are presented in Figs. 11 and 12. Fig. 11 shows results for the consonants presented in quiet and at the two speech-to-noise ratios, and Fig. 12 shows results with the questionable points removed for the +10 dB S/N. Effects of manipulations in cutoff frequency are shown in the left columns of the two figures, and effects of manipulations in rate are shown in the right columns.

As described in QPR 6 for consonants presented in quiet, increases in cutoff frequency produce increases in scores for all rates stimulation except the lowest rate of 50 pulses/s/channel, at which relatively uniform scores are obtained at the three tested cutoff frequencies (top left panel of Fig. 11). The patterns of the increases in scores with increases in cutoff frequency are similar to each other for rates of stimulation at and above 250 pulses/s/channel. The patterns are different for lower rates. Also, the scores for those lower rates are much lower than the scores for rates at and above 250 pulses/s/channel, for some or all of the tested cutoff frequencies with the lower rates. For the higher rates, scores increase more-or-less uniformly with increases in cutoff frequency up to 50 Hz.

The patterns of scores produced with increases in rate for consonants presented in quiet are relatively uniform for cutoff frequencies at and above 25 Hz (top right panel of Fig. 11). Scores for those cutoff frequencies appear to increase with increases in rate from the lowest tested rate of 50 pulses/s/channel up to 125 pulses/s/channel or higher. Scores for the lowest tested cutoff frequency of 12.5 Hz increase with increases in rate up to 250 pulses/s/channel, but are much lower than the scores for all other cutoff frequencies at rates of 100 pulses/s/channel and higher.

Results for consonants presented in conjunction with noise at the +10 dB S/N are more variable than the results for consonants presented in quiet (compare top and middle rows of Fig. 11). The patterns of scores produced with manipulations in cutoff frequency for the +10 dB S/N do not cluster together for rates at and above 250 pulses/s/channel, as observed for consonants presented in quiet. Instead, most scores increase with progressively higher rates over the range of cutoff frequencies from about 125 Hz to the upper limit of 2000 Hz. The patterns also suggest effects of changes in cutoff frequencies over certain ranges. Scores are approximately the same between the two lowest tested cutoff frequencies of 12.5 and 25 Hz, for most of the rates. Scores increase with increases in cutoff frequency from 25 to 125 Hz, for rates at and above 1000 pulses/s/channel. This general increase with increases in cutoff is more apparent with the questionable points removed (compare the middle left panel of Fig. 11 with the left panel of Fig. 12). Scores are approximately the same across cutoff frequencies from 125 to 1000 Hz, for rates at and above 2000 pulses/s/channel. With the further increase in cutoff frequency, from 1000 to 2000 Hz, scores appear to drop.

With the questionable points removed, the 50 pulses/s/channel rate clearly produces the lowest scores over the range of cutoff frequencies tested at that rate. In addition, the variability among scores, across cutoff frequencies and for the different rates, appears to be somewhat lower in the panel with the questionable points removed (left panel of Fig. 12), compared with the panel

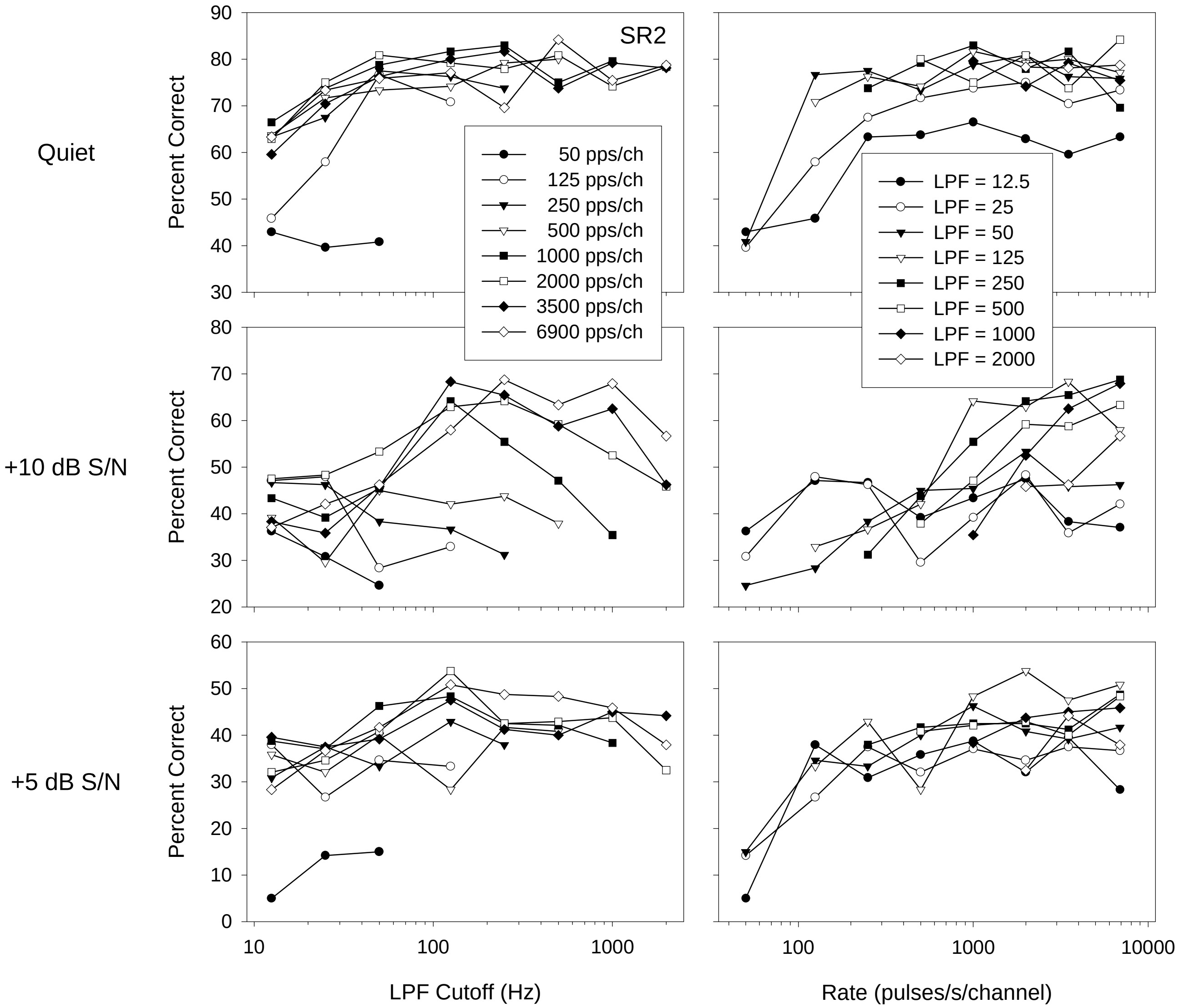

Fig. 11. Slices through the rate/cutoff frequency data for subject SR2, from tests of consonant identification using the male talker and with the consonants presented in quiet and in competition with speech-spectrum noise at the speech-to-noise ratios of +10 and +5 dB. The left column shows slices along rows in the matrices of the percent correct scores for this subject (Fig. A.3), and the right column shows slices along columns in the matrices. Plots in the left column indicate the dependence of scores on cutoff frequency while holding the rate of stimulation constant, whereas plots in the right column indicate the dependence of scores on rate of stimulation while holding the cutoff frequency constant. Standard errors of the means for the scores ranged from 1.2 to 4.7 percent and are presented in Fig. A.3. The legend for the left column indicates rates of stimulation in pulses/s/channel (pps/ch), and the legend in the right column indicates envelope cutoff frequencies in Hz (LPF). All of the data collected for the +10 dB speech-to-noise ratio are presented in this figure. Fig. 12 shows the data for that noise condition with the questionable points (identified in Fig. 10) removed.

+10 dB S/N

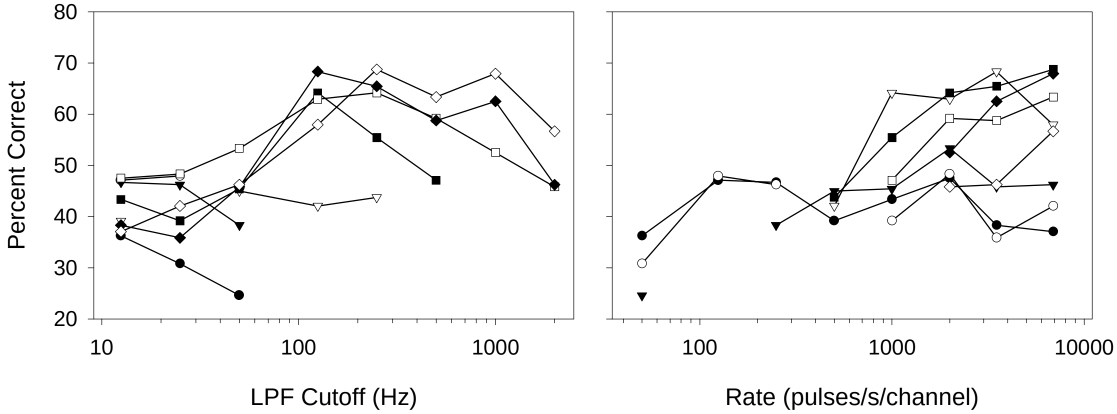

Fig. 12. Panels like those in Fig. 11 for the +10 dB speech-to-noise ratio, but with the questionable points (identified in Fig. 10) removed. Symbols are the same as those in Fig. 11.

presenting all of the collected data (left middle panel of Fig. 11). The impression of a drop in scores with increases in cutoff frequency beyond 500 or 1000 Hz is stronger in the panel with all of the collected data than in the panel with the questionable points removed.

Increases in rate appear to produce increases in scores over wide ranges of the tested rates for consonants presented at +10 dB S/N (right middle panel of Fig. 11). This is most evident for the cutoff frequencies of 250 to 1000 Hz, for which monotonic and generally large increases in scores are observed across the ranges of cutoff frequencies tested with those rates. Scores for the two lowest cutoff frequencies show a different pattern with the manipulations in rate. They increase with the increase in rate from 50 to 125 pulses/s/channel, but then vary together below and up to the level obtained at 125 pulse/s/channel, with further increases in rate. This observation holds with and without the questionable points removed.

The patterns of scores for consonants presented with noise at the +5 dB S/N appear to be less variable than the patterns at the +10 dB S/N (compare bottom and middle rows in Fig. 11). However, the overall dependence of scores on changes in cutoff frequency appears to be similar for the two speech-to-noise ratios. In both cases, the increase in cutoff frequency from 12.5 to 25 Hz does not seem to affect scores for most of the tested rates. Increases in cutoff frequency from 25 to 100 Hz appear to produce increases in scores at both S/Ns, for most or all rates at and above 1000 pulses/s/channel. Further increases in cutoff frequency up to 1000 Hz do not produce changes in scores for either S/N, with the possible exception of a decrement in scores with increases in cutoff frequency for the 1000 pulses/s/channel rate tested at the +10 dB S/N. The final increase cutoff frequency from 1000 Hz to 2000 Hz appears to produce a drop in scores for both sets of data.

Scores for the various cutoff frequencies tested at the 50 pulses/s/channel rate are much lower than all other scores for the +5 dB S/N. This finding is consistent with the findings for consonants presented in quiet and at the +10 dB S/N.

Increases in rate appear to produce increases in scores over much or all of the tested range of rates for the +5 dB S/N (see bottom right panel of Fig. 11). Scores for the different cutoff frequencies vary together with the changes in rate. Scores across rates for the lowest tested cutoff frequency of 12.5 Hz are not significantly lower than the scores for higher cutoff frequencies, except at the extreme rates of 50 and 6900 pulses/s/channel.

The averages of scores in Figs. 11 and 12 are shown in Fig. 13. The left column of Fig. 13 presents averages for all tested rates of stimulation above 200 pulses/s/channel (as in Figs. 5 and 6) versus cutoff frequency. The right column of Fig. 13 presents averages for all tested cutoff frequencies at and above 25 Hz (also as in Figs. 5 and 6) versus rate of stimulation. The gray symbols and lines in the middle panels of Fig. 13 show the averages computed with the questionable scores removed for the +10 dB S/N case.

One-way ANOVAs were conducted for each set of averages in Fig. 13. The results are presented in Table 5. All of the ANOVAs were significant except the one for the averages across cutoff frequencies for the +10 dB S/N with all points included (middle left panel of Fig. 13, black symbols and lines). That ANOVA just failed to attain significance ($p = 0.073$). (The variabilities associated with each average are higher with all points included, and the differences among the averages are lower with all points included, each of which reduces the F value for the ANOVA.)

Results from *post hoc* tests (also presented in Table 5) identify effects of manipulations in both cutoff frequency (left column of Fig. 13) and rate of stimulation (right column of Fig. 13). Effects of manipulations in cutoff frequency include significant increases in scores with increases in cutoff frequency up to 50 Hz for consonants presented in quiet. The score at 25 Hz is significantly higher than the score at 12.5 Hz, and the score at 50 Hz is significantly higher than the score at 25 Hz. Further increases in cutoff frequency do not produce further significant increases in scores.

The addition of noise interference alters the pattern of averages across cutoff frequencies. For the both the +10 and +5 dB S/Ns, averages are not significantly different between the 12.5 and 25 Hz cutoffs. Averages for cutoffs between 125 and 1000 Hz are, however, significantly higher than the averages for lower cutoffs. For the +10 dB S/N with the questionable points removed, averages for cutoffs in the range from 125 to 1000 Hz are significantly higher than averages for each cutoff up to 50 Hz, and for the +5 dB S/N, averages for cutoffs in that upper range are significantly higher than averages for each cutoff up to 25 Hz.

A further increase in cutoff frequency, from 1000 to 2000 Hz, produces a significant drop in averages for the +5 dB S/N. In particular, the average at the 125 Hz cutoff is significantly higher than the average at 2000 Hz. (The similar drop at 2000 Hz for the +10 dB S/N is not significant.)

The patterns of averages across rates of stimulation also are affected by noise interference. In quiet, averages at 500 pulses/s/channel and above are significantly higher than the averages at 50 and 125 pulses/s/channel. Also, the averages at 125 and 250 pulses/s/channel are higher than the average at 50 pulses/s/channel. The highest rate beyond which further increases in averages are not produced with further increases in rate is 500 pulses/s/channel.

The patterns for consonants presented in noise show advantages of higher rates of stimulation. For the +10 dB S/N with all points included, averages at 2000 pulses/s/channel and above are significantly higher than the averages for all rates from 50 to 500 pulses/s/channel. In addition, the average at 1000 pulses/s/channel is higher than the average at 50 pulses/s/channel.

For the +10 dB S/N with the questionable points removed, averages at 1000 pulses/s/channel and above are significantly higher than the average at 50 pulses/s/channel. For the +5 dB S/N, the average at the highest tested rate of 6900 pulses/s/channel is significantly higher than the averages at 50, 125 and 500 pulses/s/channel. Also, the averages for rates from 1000 to 3500 pulses/s/channel are higher than the averages at 50 and 125 Hz, and the averages for rates from

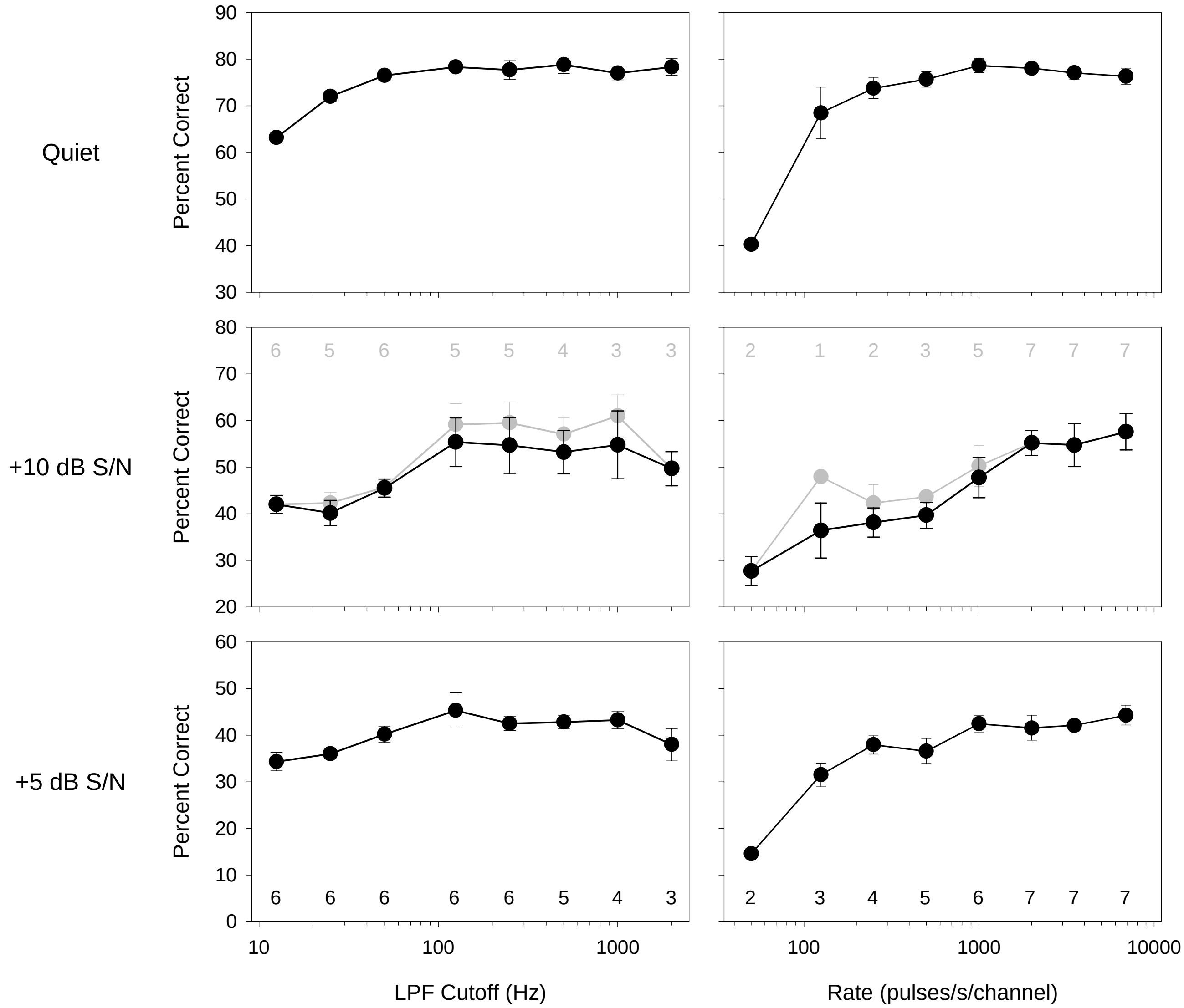

Fig. 13. Averages of scores derived from data in Figs. 11 and 12., for subject SR2. The plots in the left column of the present figure show the averages of scores for all tested rates of stimulation above 200 pulses/s/channel (i.e., 250 pulses/s/channel and higher for this subject), and the plots in the right column show the averages of scores for all tested cutoff frequencies at and above 25 Hz. The gray symbols and lines show results with the questionable points removed (for the +10 dB speech-to-noise ratio). The numbers in the bottom panels for each column indicate the number of scores included in calculations of the means for each cutoff frequency (left column) or each rate (right column). The gray numbers in the middle panels indicate those numbers for the calculations with the questionable points removed. The bars show standard errors of the means.

125 to 500 pulses/s/channel are higher than the average at 50 pulses/s/channel. In all, the results demonstrate improvements in the averages with increases in rate up to 500 pulses/s/channel for consonants presented in quiet, up to 1000 or 2000 pulses/s/channel for consonants presented at the +10 dB S/N, and up to 1000 pulses/s/channel for consonants presented at the +5 dB S/N. The further increment in averages at 6900 pulses/s/channel for the +5 dB S/N suggests the possibility that even higher rates may have been helpful there.

Table 5. Significant differences among scores for the cutoff frequency and rate of stimulation conditions presented in Fig. 13 (data for subject SR2). The differences indicated are those identified by the Fisher LSD criterion ($p < 0.05$). Entries for cutoff frequencies are in Hz, and entries for rate of stimulation are in pulses/s/channel.

Noise Condition	Manipulation	ANOVA	Significant Differences
Quiet	Cutoff frequency	$p < 0.001$	2000, 1000, 500, 250, 125, 50 > 25, 12.5 25 > 12.5
+10 dB S/N, all points		NS	
+10 dB S/N, questionable points removed		$p < 0.001$	1000, 500, 250, 125 > 50, 25, 12.5
+5 dB S/N		$p < 0.01$	125 > 2000, 25, 12.5 1000, 500, 250 > 25, 12.5
Quiet	Rate	$p < 0.001$	6900, 3500, 2000, 1000, 500 > 125, 50 250, 125 > 50
+10 dB S/N, all points		$p < 0.001$	6900, 3500, 2000 > 500, 250, 125, 50 1000 > 50
+10 dB S/N, questionable points removed		$p < 0.01$	6900, 3500, 2000, 1000 > 50
+5 dB S/N		$p < 0.001$	6900 > 500, 125, 50 3500, 2000, 1000 > 125, 50 500, 250, 125 > 50

Discussion

The present study extended a prior study to evaluate effects of changes in stimulus rate and envelope cutoff frequency on the speech reception performance of CIS processors. The present study included (1) tests of consonant identification using a female talker, for two subjects previously tested with a male talker; (2) tests of sentence recognition for those same two subjects; and (3) tests of consonant identification in noise using the male talker, for another of the previously-tested subjects. Many combinations of rates and cutoff frequencies were included in each set of tests.

Results from the tests with the female talker were similar to the prior results with the male talker. The contour plots of percent correct scores for the female talker had the same general shape as the plots for the male talker, for both subjects. Combinations of low rates and low cutoff frequencies produced large decrements in scores for both talkers and both subjects. Conversely, the highest scores for both talkers and both subjects were obtained at the highest tested rates and at intermediate cutoff frequencies. Patterns of scores for the combined male and female talkers were only somewhat different from the patterns for the male talker, described before in QPR 6.

Although some differences were noted in the patterns of scores between the male and female talkers for each of the subjects, the results did not provide evidence of a consistent talker effect for the conditions of the present and prior studies. The present results with the female talker confirm and extend the prior results with the male talker.

Results from the tests of sentence recognition were consistent with the results from the consonants tests for subject SR9 but not for subject SR10. Sentence scores for SR9 ranged from 29 to 68 percent correct across the various combinations of rate and cutoff frequency, whereas the scores for SR10 ranged from 80 to 98 percent correct, with most of those scores at 90 or higher. Ceiling effects may have limited the sensitivity of the sentence test for SR10. If so, this would explain the differences in the patterns of consonant and sentence scores for him.

The results from the sentence tests verify and extend the prior results (from the consonant tests with the male talker) for subject SR9. In contrast to the results from the consonant tests, scores from the sentence tests for subject SR10 are not significantly different across the various combinations of rate and cutoff frequency. This lack of significance may be attributable to ceiling effects in the sentence tests for this subject.

Patterns of scores from the final set of tests showed that both higher cutoff frequencies and higher rates are advantageous for consonant identification in noise, compared with consonant identification in quiet. In quiet, scores improved with increases in rate up to 500 pulses/s/channel and with increases in cutoff frequency up to 50 Hz. At the S/N of +10 dB, these points of asymptotic performance were 1000 or 2000 pulses/s/channel and 125 Hz, respectively (the two numbers for rate correspond to results from analyses with and without the questionable points removed). At the S/N of +5 dB, the points were 1000 pulses/s/channel and 125 Hz, with a suggestion that even higher rates (at or beyond the upper limit of the tested rates) might be helpful. At that S/N, a decrement in scores also was observed with the increase in cutoff frequency from 1000 to 2000 Hz (the upper limit of tested cutoffs). Possibly, an especially high cutoff frequency may degrade performance in noise, in that such a cutoff might allow interference from high-frequency and random variations in the noise, whereas lower cutoffs might reduce or eliminate the influence of high-frequency variations.

One of the major problems associated with present implant systems is the great difficulty their users experience in listening to speech in noise. The present results suggest that this difficulty may be substantially reduced through the use of relatively high rates and relatively high cutoff frequencies in the speech processors used with these systems.

III. Plans for the next quarter

Our plans for the next quarter include the following:

- Studies with two recipients of bilateral COMBI 40+ implants, referred to us by our colleagues at the Julius-Maximilians Universität in Würzburg, Germany. Studies with subject ME4 are scheduled for the two weeks beginning on July 17, and studies with subject ME5 are scheduled for the three weeks beginning on July 31. Joachim Müller, M.D., plans to participate in part of the studies with subject ME5. The studies with both subjects will include measures of sensitivities to interaural timing and amplitude differences and evaluation of various processing strategies designed to represent cues for sound localization or to exploit the availability of bilateral electrodes in other ways (see Quarterly Progress Report 4 for this project, for a detailed discussion of processing options for bilateral implants).
- Studies with a recipient of a relatively short array of electrodes (a Med El COMBI 40+ implant intentionally inserted only 20 mm into the scala tympani) whose low frequency residual hearing in the same ear also is preserved. This subject, ME6, was referred to us by our colleagues at the J.W. Goethe Universität in Frankfurt, Germany, and is scheduled for two weeks of studies in our laboratory, beginning on August 28. Thomas Pfennigdorff, M.D., of the Frankfurt group, will participate in the studies. The studies will include evaluation of various strategies for combined electric and acoustic stimulation of the same cochlea.
- Studies with a recipient of bilateral CI24M implants, referred to us by our colleagues at the University of Iowa. Studies with this subject, NU6, are scheduled for the two weeks beginning on September 18. The studies will include measures of sensitivities to interaural timing and amplitude differences and evaluation of various processing strategies designed to represent cues for sound localization or to exploit the availability of bilateral electrodes in other ways (see Quarterly Progress Report 4 for this project, for a detailed discussion of processing options for bilateral implants).
- A visit by Reinhold Schatzer to Fishkill, NY, to work with Marian Zerbi in the further development of software for simultaneous control of bilateral CI24M implants using the Cochlear Corporation's embedded protocol for those devices. The trip is scheduled for July 5-7.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

IV. Acknowledgments

We thank subjects SR3, ME3, SR1 and SR8 for their participation in the studies of this quarter. We also would like to thank again subjects SR2, SR9 and SR10 for their participation in the studies of prior quarters, as described in section II of this report. We are grateful for the many contributions made by Raymond Mederake in the studies with subject ME3.

V. Erratum for Quarterly Progress Report 6

Table 1 in QPR 6 for this project did not include a reference to Lawson *et al.*, 1993 (Quarterly Progress Report 2, NIH project N01-DC-2-2410). This study predated all studies that were included in the original table. A revised Table 1 is presented below. The results presented in Lawson *et al.*, 1993, do not alter the conclusions of QPR 6.

Study	Subjects	Channels	Rate(s)	LPF Cutoff(s)	Test(s)
Brill *et al.*, 1997	2	2 3 4 6 8 10	1515, 9090 1515, 6060 1515, 4545 1515, 3030 1515, 2273 1515, 1818	400	HSM sent. w. lipreading, subj. MK; 2-digit numbers, subj. FZ
Brill *et al.*, 1998	1 5 4	8 6 4	625, 694, 781, 893, 1042, 1250, 1515 400, 800, 1515, 3030 800, 1515, 3030, 4545	400 for rates of 1515 and higher; ¼ the rate for lower rates	16 consonants monosyllabic words monosyllabic words or 2-digit numbers
Fu & Shannon, 2000	6	4	50, 100, 150, 200, 300, 400, 500 500	40 % of the rate 2, 5, 10, 20, 40, 80, 160	12 vowels, 16 consonants
Kiefer *et al.*, 2000	12 6	4 5 or 6 7 or 8 7 or 8 4	600, 1200, 1515-1730, max rate 1515-1730, max rate 600, 1200, 1515-1730 600 max rate	400 200 26.67 % of the rate	8 vowels, 16 consonants, monosyllabic words
Lawson *et al.*, 1993	1	4	417 627 2525	50, 200, 800 50, 200 50, 200, 800	24 consonants
Lawson *et al.*, 1996	5	6	250, 833, 2525 833	200 400	16 or 24 consonants, dep. on subj.
Loizou & Poroy, 1999	6	6	400, 800, 1400, 2100	100, 200, 400 and 400, respectively	11 vowels, 20 consonants, monosyllabic words
Pelizzone *et al.*, 1998	4	5	2000, 20000	400	7 vowels, 14 consonants

Table 1. Prior and contemporaneous studies on effects of changes in stimulus rate and envelope cutoff frequency for CIS processors.

Appendix 1. Summary of reporting activity for this quarter

Reporting activity for this quarter, covering the period of April 1 through June 30, 2000, included the following presentations:

Brill S: Electrode discrimination along the cochlea based on pitch perception. Invited talk presented at the Biweekly Meeting of the Duke/RTI Cochlear Implant Team, Duke University Medical Center, Durham, NC, May 28, 2000.

Wilson BS, Lawson DT, Brill S, Wolford RD and Schatzer R: Binaural cochlear implants. Invited lecture presented at the *Conference on Binaural Hearing, Hearing Loss, Hearing Aids, & Cochlear Implants*, Iowa City, IA, June 22-24, 2000.

Tyler R, Parkinson A, Gantz B, Rubinstein J, Wilson B, Witt S, Wolaver A, Lowder M: Independent binaural cochlear implants. Invited lecture presented at the *Conference on Binaural Hearing, Hearing Loss, Hearing Aids, & Cochlear Implants*, Iowa City, IA, June 22-24, 2000.

Appendix 2. Supplemental data for Section II

Male Talker

SR9

Rate (pulses/s/channel) \ Lowpass Cutoff (Hz)	12.5	25	50	100	200	400	800	1600
50	47.5 ±3.5	44.4 ±2.0	50.6 ±4.1					
100	56.3 ±2.6	68.1 ±2.9	68.8 ±2.6	54.4 ±3.5				
200	53.1 ±3.7	70.6 ±4.3	67.5 ±2.5	63.4 ±2.5	66.9 ±2.3			
417	45.6 ±3.5	69.4 ±3.7	63.8 ±3.0	63.8 ±2.8	61.3 ±3.0	66.9 ±3.5		
833	58.1 ±3.8	62.5 ±3.4	65.6 ±3.5	78.1 ±3.4	78.1 ±2.1	63.8 ±1.3	73.1 ±2.6	
1634	60.0 ±3.4	71.3 ±4.0	73.8 ±3.6	71.9 ±4.8	76.3 ±3.3	70.0 ±2.9	71.9 ±3.1	71.9 ±2.3
2525	63.8 ±4.2	78.8 ±2.8	64.4 ±3.6	70.6 ±3.5	75.6 ±4.3	64.4 ±4.8	71.9 ±3.4	69.4 ±3.0

SR10

Rate (pulses/s/channel) \ Lowpass Cutoff (Hz)	50	100	200	400	800
100	55.4 ±3.0				
200	67.1 ±3.9	68.8 ±4.0			
417	69.6 ±2.4	70.4 ±1.9	71.3 ±2.9		
833	69.6 ±2.2	72.5 ±2.4	64.2 ±2.7	70.4 ±3.8	
1634	67.1 ±3.1	80.8 ±2.9	87.1 ±2.7	81.7 ±1.8	79.2 ±2.5

Female Talker

SR9

Rate (pulses/s/channel) \ Lowpass Cutoff (Hz)	12.5	25	50	100	200	400	800	1600
50	38.8 ±4.0	47.5 ±2.8	40.6 ±4.1					
100	41.3 ±4.0	48.1 ±3.5	43.4 ±2.9	40.6 ±3.1				
200	38.1 ±4.6	41.3 ±4.9	49.1 ±3.1	47.2 ±3.7	45.6 ±2.8			
417	34.4 ±4.5	44.4 ±2.0	41.9 ±2.4	39.1 ±3.1	43.8 ±2.3	36.9 ±2.7		
833	42.5 ±3.8	38.8 ±2.4	45.6 ±4.6	51.9 ±4.7	45.6 ±3.1	47.8 ±2.6	42.5 ±4.1	
1634	40.0 ±4.6	52.5 ±4.0	43.8 ±2.6	41.9 ±3.2	48.8 ±4.6	50.0 ±4.2	50.6 ±4.8	56.3 ±4.9
2525	50.6 ±4.8	58.1 ±2.5	54.4 ±3.2	56.9 ±3.4	56.9 ±2.9	55.0 ±2.9	50.6 ±4.1	54.4 ±2.6

SR10

Rate (pulses/s/channel) \ Lowpass Cutoff (Hz)	50	100	200	400	800
100	61.7 ±2.6				
200	77.9 ±1.9	78.8 ±2.0			
417	82.9 ±2.8	78.8 ±2.4	84.2 ±2.2		
833	77.5 ±1.5	78.3 ±2.5	77.5 ±2.9	78.3 ±2.7	
1634	78.8 ±2.1	86.3 ±3.0	80.4 ±2.1	85.0 ±1.8	77.1 ±1.6

Both Talkers

SR9

Rate (pulses/s/channel) \ Lowpass Cutoff (Hz)	12.5	25	50	100	200	400	800	1600
50	43.1 ±2.8	45.9 ±1.7	45.6 ±3.0					
100	48.8 ±2.9	58.1 ±3.2	56.1 ±2.8	47.5 ±2.8				
200	45.6 ±3.3	55.9 ±4.6	58.3 ±2.5	55.3 ±2.5	56.3 ±3.0			
417	40.0 ±3.1	56.9 ±3.5	52.8 ±2.6	51.4 ±2.9	52.5 ±2.3	51.9 ±4.1		
833	50.3 ±3.2	50.6 ±3.4	55.6 ±3.6	65.0 ±4.1	61.9 ±4.2	56.3 ±2.2	57.8 ±4.3	
1634	50.0 ±3.6	61.9 ±3.5	58.8 ±4.1	56.9 ±4.4	62.5 ±4.2	60.0 ±3.4	61.3 ±3.7	64.1 ±3.2
2525	57.2 ±3.5	68.4 ±3.0	59.4 ±2.6	63.8 ±2.9	66.3 ±3.3	59.7 ±2.9	61.3 ±3.6	61.9 ±2.6

SR10

Rate (pulses/s/channel) \ Lowpass Cutoff (Hz)	50	100	200	400	800
100	58.5 ±2.1				
200	72.5 ±2.4	73.8 ±2.5			
417	76.3 ±2.4	74.6 ±1.8	77.7 ±2.3		
833	73.5 ±1.6	75.4 ±1.8	70.8 ±2.5	74.4 ±2.4	
1634	72.9 ±2.3	83.5 ±2.1	83.8 ±1.8	83.3 ±1.3	78.1 ±1.4

Fig. A.1. Percent correct scores and standard errors of the means for identification of consonants in quiet, male and female talkers, subjects SR9 and SR10.

CUNY Sentences

SR9

Rate (pulses/s/channel)	50	100	200	400	800
100	29.2 ±4.2				
200	59.1 ±4.4	42.9 ±5.0			
417	60.3 ±3.6	61.5 ±7.1	59.6 ±4.3		
833	39.5 ±4.7	60.5 ±5.3	59.9 ±3.9	56.4 ±4.4	
1634	45.8 ±2.9	66.7 ±5.4	61.3 ±3.4	63.5 ±3.1	68.1 ±4.8

Lowpass Cutoff (Hz)

SR10

Rate (pulses/s/channel)	50	100	200	400	800
100	79.9 ±7.7				
200	89.0 ±4.3	94.4 ±0.5			
417	90.4 ±3.6	87.0 ±6.4	90.0 ±2.9		
833	88.5 ±2.2	95.1 ±2.8	86.3 ±2.4	97.5 ±1.6	
1634	87.5 ±4.8	95.3 ±2.4	95.8 ±2.8	93.6 ±2.0	89.5 ±2.2

Lowpass Cutoff (Hz)

Fig. A.2. Percent correct scores and standard errors of the means for recognition of CUNY sentences in quiet, male talker, subjects SR9 and SR10.

SR2

Quiet

Rate (pulses/s/channel)	12.5	25	50	125	250	500	1000	2000
50	42.9 ±3.3	39.6 ±3.8	40.8 ±1.7					
125	45.8 ±2.9	57.9 ±2.2	76.7 ±2.1	70.8 ±2.2				
250	63.3 ±3.1	67.5 ±2.1	77.5 ±1.9	76.3 ±2.3	73.8 ±1.4			
500	63.8 ±2.0	71.1 ±3.7	73.3 ±2.4	74.2 ±1.5	79.2 ±2.0	80.0 ±1.6		
1000	66.5 ±2.2	73.8 ±3.2	78.8 ±1.8	81.7 ±4.0	82.9 ±1.5	75.0 ±2.9	79.6 ±2.0	
2000	62.9 ±2.4	75.0 ±2.2	80.8 ±2.5	79.2 ±1.8	77.9 ±3.2	80.8 ±1.3	74.2 ±2.6	78.3 ±2.0
3500	59.6 ±2.5	70.4 ±2.3	76.3 ±2.3	80.0 ±1.9	81.7 ±2.2	73.8 ±3.0	79.2 ±1.2	78.1 ±2.0
6900	63.3 ±2.5	73.3 ±1.3	75.8 ±2.0	77.1 ±1.9	69.6 ±3.0	84.2 ±2.4	75.4 ±1.8	78.8 ±2.3

+10 dB S/N

Rate (pulses/s/channel)	12.5	25	50	125	250	500	1000	2000
50	36.3 ±2.3	30.8 ±2.4	24.6 ±2.2					
125	47.1 ±1.8	47.9 ±4.6	28.3 ±2.3	32.9 ±3.3				
250	46.7 ±2.3	46.3 ±2.7	38.3 ±1.6	36.7 ±2.8	31.3 ±3.6			
500	39.2 ±2.2	29.6 ±2.6	45.0 ±2.7	42.1 ±1.2	43.8 ±3.3	37.9 ±1.9		
1000	43.3 ±2.3	39.2 ±3.6	45.4 ±2.7	64.2 ±3.1	55.4 ±2.6	47.1 ±2.3	35.4 ±4.1	
2000	47.5 ±3.4	48.3 ±2.6	53.3 ±1.4	62.9 ±1.8	64.2 ±3.6	59.2 ±2.8	52.5 ±2.4	45.8 ±2.4
3500	38.3 ±2.7	35.8 ±4.7	45.8 ±1.9	68.3 ±1.8	65.4 ±2.9	58.8 ±2.9	62.5 ±2.3	46.3 ±2.4
6900	37.1 ±3.2	42.1 ±2.2	46.3 ±4.0	57.9 ±2.9	68.8 ±3.5	63.3 ±2.3	67.9 ±2.9	56.7 ±2.3

+5 dB S/N

Rate (pulses/s/channel)	12.5	25	50	125	250	500	1000	2000
50	5.0 ±1.4	14.2 ±2.2	15.0 ±2.2					
125	37.9 ±2.9	26.7 ±2.5	34.6 ±2.6	33.3 ±1.6				
250	30.8 ±3.7	37.5 ±3.9	33.3 ±2.6	42.9 ±2.5	37.9 ±2.4			
500	35.8 ±2.7	32.1 ±2.9	40.0 ±4.4	28.3 ±3.6	41.7 ±2.8	40.8 ±1.2		
1000	38.8 ±2.5	37.1 ±2.8	46.3 ±3.6	48.3 ±2.5	42.5 ±2.1	42.1 ±3.1	38.3 ±2.0	
2000	32.1 ±2.1	34.6 ±2.7	40.8 ±4.2	53.8 ±3.1	42.5 ±3.3	42.9 ±2.4	43.8 ±3.0	32.5 ±3.7
3500	39.6 ±4.6	37.5 ±2.5	39.2 ±3.2	47.5 ±2.6	41.3 ±2.2	40.0 ±2.5	45.0 ±2.5	44.2 ±3.1
6900	28.3 ±2.8	36.7 ±3.4	41.7 ±2.9	50.8 ±2.8	48.8 ±3.5	48.3 ±2.9	45.8 ±1.6	37.9 ±2.3

Lowpass Cutoff (Hz)

Fig. A.3. (Please see caption on next page.)

Fig. A.3. Percent correct scores and standard errors of the means for identification of consonants in quiet and in competition with speech-spectrum noise at the speech-to-noise ratios of +10 and +5 dB, male talker, subject SR2. Some of the scores for the tests at the speech-to-noise ratio of +10 dB are questionable and these scores (and associated processor conditions) are identified in Fig. 10.