Sixth Quarterly Progress Report

January 1 through March 31, 2000

NIH Project N01-DC-8-2105

Speech Processors for Auditory Prostheses

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CONTENTS

I. Introduction 3

II. Effects of changes in stimulus rate and envelope cutoff frequency for CIS processors 5

III. Plans for the next quarter..52

IV. Announcements..53

V. Acknowledgments..54

Appendix 1: Summary of reporting activity for this quarter..55

Appendix 2: "Mini Symposium on Cochlear Implants," held at RTI on Feb 7, 2000...................56

Appendix 3: Supplemental data for Section II 57

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:

- Ongoing studies with Ineraid subject SR2. Studies in this quarter included (1) evaluation of the TIMIT speech database as a source of difficult sentences for sensitive measures of speech reception by a high-performance subject; (2) application of that database in further measures of effects of changes in several CIS processor parameters, including mapping function exponent, rate of stimulation, and cutoff frequency for the lowpass filters in the envelope detectors; (3) further evaluation of effects of changes in the mapping function exponent, using CUNY sentences presented in quiet and in noise; and (4) recordings of intracochlear evoked potentials for single polarities of stimulation, with biphasic pulses and with "split phase" biphasic pulses with 3 ms between the first and second phases. (The TIMIT database proved to be both difficult and reliable. We anticipate extensive use of that database as a source of test material in future studies.)
- Studies with Ineraid subject SR15 during the week beginning on February 7. The studies included (a) longitudinal measures with her portable CIS (CIS-Link) processor, (b) measures of consonant identification for CIS processors using a wide range of exponents for the mapping function, and (c) evaluation of combinations of low stimulus rates and low cutoff frequencies for the envelope detectors in CIS processors, as suggested by prior psychophysical scaling results for this subject. (Those prior results, some of which are presented in Quarterly Progress Report 8 for NIH project N01-DC-5-2103, indicated especially poor access to within-channel rate and frequency information for this subject.)
- Continued development of a new strategy, designed to mimic closely the nonlinear processing in the peripheral auditory system, including the strong and nearly instantaneous compression at the basilar membrane for sound pressure levels above 35-40 dB and the strong and noninstantaneous (with multiple time constants) compression that occurs at the synapse between inner hair cells and type I fibers of the auditory nerve.
- A visit by Jan Kiefer and Thomas Pfennigdorff, of the J.W. Goethe Universität in Frankfurt, Germany, on February 1 and 2, for further discussions on combined electric and acoustic stimulation of the same cochlea and for further development of plans for cooperative studies between the university and RTI. (This visit follows one by Blake Wilson to Frankfurt; see Quarterly Progress Report 5 for this project.)
- Continued preparation for studies with recipients of CI24M implants on both sides, and with recipients of COMBI 40+ implants on both sides (preparation principally by Stefan Brill and Marian Zerbi, with contributions by other members of the team).
- A visit by Marian Zerbi to assist in the above preparation (February 7-9).
- A separate visit by Zerbi on March 11-16, principally to transfer knowledge about use and programming of the laboratory systems to Reinhold Schatzer, a new member of the project team who began work at RTI on March 1 (see Announcements section of this report).
- Presentation of project results in an invited lecture at the *6th International Cochlear Implant Conference*, Miami Beach, FL February 3-5, 2000.

- Visits by Joachim Müller of the Julius-Maximilians Universität in Würzburg, Peter Nopp of the Med El company in Innsbruck, and Arturs Lorens of the Institute of Physiology and Pathology of Hearing in Warsaw, following the Miami conference.
- A *Mini Symposium on Cochlear Implants* at RTI, held in conjunction with the above visits (February 7). (The agenda for the symposium is presented in Appendix 2 to this report.)
- Detailed discussions with Dr. Müller during his visit, on the scheduling of his patients for cooperative studies at RTI.
- A visit by Jim Patrick on March 2, in part to discuss upcoming studies at RTI of 4-6 subjects implanted with an experimental version of the Nucleus device, that includes the new "modiolar hugging" electrode array developed by Cochlear Pty. Ltd., in conjunction with a percutaneous connector.
- Continued development of an Access database of processor designs and study results, to bring this information together in one place for fast access and in a structure that will allow retrieval of prior designs and results on the basis of shared attributes and parameter values. (Work in this quarter included development of "front end translators," written in Visual Basic, for automated reading of previously-recorded specification files for processors into the Access database.)
- 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 to evaluate effects of manipulations in rate of stimulation, and in the cutoff frequency for the lowpass filters in the envelope detectors, in CIS processors. These studies included extensive manipulations over two-dimensional spaces of rate and lowpass filter cutoff for four subjects. Results from other studies indicated in the list above will be presented in future reports.

II. Effects of changes in stimulus rate and envelope cutoff frequency for CIS processors

The amount and quality of information transmitted within channels in a cochlear implant might be increased in any of several ways, including reinstatement of spontaneous-like activity in the auditory nerve with use of high-rate "conditioner" pulses (Rubinstein *et al.*, 1999; Wilson, 2000a), reinstatement of information that is discarded in the envelope detectors of continuous interleaved sampling (CIS) and other speech processors for cochlear prostheses (Eddington, 1999), or increases in the range and fidelity of temporal variations represented in the stimuli for each channel through use of high carrier rates and high cutoff frequencies for the envelope detectors (Wilson *et al.*, 1994; Wilson, 1997a and 2000a). Our focus here is on this last possibility, *i.e.*, evaluation of effects of manipulations in carrier rate and in the envelope cutoff frequency for CIS processors.

Background

As described in several recent reports (Wilson *et al.*, 1994; Wilson *et al.*, 1997a; Wilson, 1997 and 2000a), responses of the human auditory nerve to electrical stimuli reflect the modulation frequency of sinusoidally-amplitude-modulated (SAM) pulse trains up to roughly ¼ the carrier rate. The representation of higher modulation frequencies is complex and does not bear a simple, one-to-one relationship with the modulation waveform. Busby and coworkers also have observed distortions in the perception of modulation frequencies for frequencies above ¼ the carrier rate (Busby *et al.*, 1993).

Large qualitative changes in the neural representation of the modulation waveform are produced when the modulation frequency approaches or exceeds ½ the carrier rate, the Nyquist frequency. The neural representation for these frequencies is quite unlike the modulation waveform, for a wide range of carrier rates.

High carrier rates allow simple representations of the modulation waveform over a relatively broad range of modulation frequencies. For example, recordings of intracochlear evoked potentials show that modulation frequencies as high as 600 Hz can be represented with high fidelity using a carrier rate of 4065 pulses/s (Wilson, 1997a and 2000a). The simplification in the representation of the modulation waveform with high carrier rates probably is produced by (1) an increase in the resolution of sampling of the waveform by the carrier pulses and (2) a more stochastic pattern of responses in auditory neurons with carrier rates above 3000 to 5000 pulses/s (Rubinstein *et al.*, 1999; Wilson *et al.*, 1994).

Ideally, then, one might expect that increases in carrier rate, and concomitant increases in the upper boundary of frequencies included in the modulation waveform, would improve the speech reception performance of implant patients. However, increases in carrier rate also may increase a component of electrode interactions called "temporal channel interactions." These interactions are produced by temporal summation of rapidly presented (otherwise subthreshold) pulses across electrodes, or by neural adaptation that reduces the excitability of neurons to pulses following a first suprathreshold pulse in a series of rapidly presented pulses. In the presence of either of these mechanisms, the neural response that would be produced with stimulation of one electrode (or channel) only would be different from the response produced with stimulation of that electrode in the context of rapid sequential stimulation of multiple electrodes. Such differences might degrade or distort the across-electrode, across-channel representation of the speech spectrum with multichannel implants. Thus, a tradeoff may exist between possible improvements due to simplification of the representation of the modulation waveforms within channels versus possible increases in electrode interactions with increases in rate of stimulation. Such a tradeoff might manifest itself as a peak in speech reception performance at some particular carrier rate for a given subject and number of channels.

Another consideration relating to high-rate stimuli is whether the additional range of modulation frequencies that can be represented with such stimuli can in fact be perceived. That is, can implant patients reliably scale differences in modulation frequency as differences in perceived pitch over the entire range of frequencies? If not, high-rate stimuli may not offer any advantage over lower rates that are just adequate to represent modulation frequencies at the upper end of the perceptual range. Indeed, such lower rates might be better in that their use would help to minimize electrode interactions.

As described in recent reports from our laboratory (Wilson *et al.*, 1997b and 1999b), access to frequency information presented within channels varies widely among implant patients. With high carrier rates some subjects can scale modulation frequencies up to 1000 Hz or a bit higher, whereas other subjects can scale modulation frequencies only up to 200 or 300 Hz. This suggests that high-rate stimuli, and the accompanying increase in the range of modulation frequencies that can be represented at the auditory nerve, may be helpful to some but by no means all patients. Patients who cannot perceive a broad range of frequencies within channels (even with high carrier rates) may be best served with relatively low rates of stimulation, *e.g.*, rates that are four to five times higher than the highest frequency included in the modulation waveforms, with that highest modulation frequency set at the upper end of the perceptual range.

An additional consideration is that different ranges of modulation frequencies reflect different aspects of the speech signal. Rosen for example describes three ranges temporal information in speech -- the first range from about 2 Hz to 50 Hz, reflecting the "amplitude envelope" of speech; the second range from about 50 Hz to 500 Hz, reflecting the periodicity of voiced speech and the aperiodicity of unvoiced speech; and the third range from about 500 Hz up to 10 kHz, reflecting the temporal fine structure of speech (Rosen, 1992). Among these, the ranges from 2 to 50 Hz and from 50 to 500 Hz might be represented in the modulation waveforms of conventional CIS processors.

Results from a wide variety of studies with normal-hearing subjects have indicated the critical importance of the lower range of modulation frequencies for speech reception. For example, results from studies conducted by Drullman and coworkers (1994a and b) and by Houtgast and Steeneken (1973) have shown that most (but not all) of the information in speech presented in quiet conditions can be conveyed with low frequency modulations in multiple bands, with the highest modulation frequency at 16 to 20 Hz and with the number of bands at about 8 or higher. Results from various studies also have demonstrated a tradeoff between the number of channels or bands and the representation of temporal variations within bands. In particular, an increase in the range of temporal variations within bands can compensate or partly compensate for a reduction in the number of bands (see, *e.g.*, Eddington, 1999; Eddington *et al.*, 1998).

This last point may have special relevance for implants inasmuch as the number of perceptually distinct electrodes (and corresponding channels) appears to be no higher than 4 to 6 with present designs and placements of intracochlear electrode arrays (Brill *et al.*, 1997; Fishman *et al.*, 1997; Kiefer *et al.*, 2000; Lawson *et al.*, 1996). Thus, representations of temporal variations over a wide range of frequencies may be more important for implant patients, with a limited number of channels, than for subjects with normal hearing, with 14 to 19 critical-band "channels" over the range of speech frequencies (the exact number depending on the endpoints of the defined range).

In summary, high carrier rates can simplify the representation of modulation waveforms and frequencies at the auditory nerve of implant patients. However, such rates also may exacerbate electrode interactions and thereby reduce the salience of channel-related cues. The range over which changes in modulation frequency are perceived as changes in pitch varies among implant patients. With high carrier rates some patients can perceive increases in modulation frequency as increases in pitch up to 1000 Hz or higher, whereas the pitch percept for other patients plateaus at modulation frequencies of 200 to 300 Hz. Representation of modulation frequencies beyond these "pitch saturation limits" may not be desirable. A final consideration is that modulation frequencies below 20 Hz convey most of the information about speech in processors having more than about 8 bandpass channels, at least for subjects with normal hearing and at least for processed speech signals presented in quiet conditions. Representation of higher frequencies in modulation waveforms may not produce measurable improvements in speech reception for some or all subjects using multichannel cochlear implants.

Prior and contemporaneous studies

Studies have been conducted to evaluate effects of rate manipulations, or of changes in the cutoff frequency of the envelope detectors, in CIS processors. The conditions and tests for these studies are presented in Table 1. In general, the conditions sample only a limited range of rates for each of the studies. Also, changes in the cutoff frequency of the envelope detectors were included in only in a subset of the studies, and, for those, for only one rate of stimulation. A wide range of cutoffs was included in the study of Fu and Shannon (in conjunction with the stimulus rate of 500 pulses/s/channel), but only two cutoff frequencies were included in the studies of Kiefer *et al.* (in conjunction with the stimulus rate of 600 pulses/s/channel) and of Lawson *et al.* (in conjunction with the stimulus rate of 833 pulses/s/channel).

An important purpose of the present study was to evaluate effects of changes in both rate of stimulation and in the cutoff frequency of the envelope detectors, over wide ranges of each parameter. Conditions were specified with large matrices of rate and lowpass cutoff for each of four subjects. The many tested combinations of rate and lowpass cutoff allowed us to evaluate possible interactions between the two parameters, *e.g.*, the possibility that increases in lowpass cutoff beyond a certain limit might be helpful in conjunction with high rates of stimulation but not in conjunction with low rates of stimulation.

Another purpose was to evaluate effects of increases in rate of stimulation beyond 3000 to 5000 pulses/s/channel, which might produce a more stochastic pattern of response in the auditory nerves of implant patients, compared with the deterministic responses produced with lower rates. As noted above, the stochastic patterns might improve the neural representation of the envelope signals derived by CIS processors.

Methods

This study included measures of consonant identification with multichannel CIS processors using many combinations of cutoff frequency for the envelope detectors and carrier rate. It also included (1) measures of sentence recognition with a single-channel variation of CIS processors for one of the subjects, using seven combinations of cutoff frequency and carrier rate, and (2) measures of consonant identification, word recognition, and sentence recognition with multichannel CIS processors for each of the subjects, using a fixed cutoff frequency and various carrier rates.

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.*, 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.

Subjects. Four users of the Ineraid implant served as subjects. Each had had multiple years of daily experience with CIS processors at the time of the studies.

Subjects SR2 and SR3 enjoy exceptionally high levels of speech reception performance with their implants, whereas subjects SR9 and SR10 have lower levels of performance. The asymptotes of pitch judgments for these subjects, with increases pulse rate for unmodulated pulse trains or

Subject	Unmodulated pulses (pps)	Mod Freq, 10 k pps carrier (Hz)	NU6
SR2	1000	1400 or higher	96
SR3	500	500	70
SR9	300	200	14
SR10	300	300	42

Table 2. Asymptotes of pitch judgments. The asymptotes are the point beyond which further increases in pulse rate (for unmodulated pulse trains) or further increases in modulation frequency (for sinusoidally-amplitude-modulated pulse trains with the carrier rate of 10 k pulses/s) do not produce statistically significant increases in perceived pitch. The final column in the Table lists the best NU6 score for each subject's clinical CIS processor. Additional details about these results and tests may be found in Wilson *et al.*, 1997b and 1999b.

increases in modulation frequency for SAM pulse trains with a 10 k pulses/s carrier, are presented in Table 2 (data from Wilson *et al.*, 1997b). Table 2 also lists the best score for the recognition of the NU-6 monosyllabic words for each of the subjects, using her or his clinical CIS processor, at the outset of the present study.

Processors. The design of multichannel CIS processors is described in Wilson *et al.*, 1991, and in Wilson, 2000b. In the present study, the rate of the carrier pulses and the cutoff frequency of the lowpass filters in the envelope detectors were manipulated. All other parameters were fixed in the processors for each of the subjects. Those other parameters are listed in Table 3 for the rate/lowpass cutoff series of experiments and in Table 4 for the rate/fixed lowpass cutoff series of experiments. In general, parameters other than rate or lowpass cutoff were selected to place speech scores in a sensitive range for each of the subjects. For example, the number of channels was set at four rather than six for subjects SR2 and SR3 to help reduce their scores and thereby reduce the likelihood of possible ceiling effects. The processor outputs were delivered to the implanted electrodes of the subjects through the percutaneous connector of the Ineraid device and using the stimulation equipment described below.

The single-channel variation of CIS processors used a single bandpass filter for its one channel, with an order of six and with corner frequencies at 350 and 5500 Hz. Additional parameters that were fixed across the processors included a half-wave rectifier in the envelope detector, an order of four for the lowpass filter in the envelope detector, a logarithmic mapping function, and a pulse duration of 33 μs/phase. Stimulus pulses were delivered to electrode 3 in the subject's implant (in the middle of the electrode array), with reference to a remote electrode in the temporalis muscle.

Stimulation equipment. Special equipment was designed and built to support the high rates of stimulation required for the present and related studies (van den Honert *et al.*, 1996). The isolated current sources used in prior studies in our laboratory were limited by a restricted bandwidth (approximately 60 kHz) and relatively high noise of the isolators, a limited compliance voltage (±11 volts), and shunting of high frequencies across the parasitic capacitances among the cables from the isolators to the percutaneous connectors of the subjects. In the new equipment digital isolators were used instead of analog isolators, that effectively eliminated the bandwidth and noise limitations of the latter. The compliance voltage was increased to ±58 volts, which allowed specification of short-duration pulses (as short as 5 μs/phase) that also were capable of

Subject	Channels	Pulse Dur (μs)	Mapping	Rectifier
SR2	4	18	log	Halfwave
SR3	4	18	log	Halfwave
SR9	6	33	0.1	Fullwave
SR10	6	33	0.1	Fullwave

Table 3. Parameters of CIS processors used in the rate/lowpass cutoff series of experiments. The third column lists the pulse duration per phase in microseconds, and the fourth column lists the nonlinear mapping function used for each of the subjects. Logarithmic mapping is indicated by a "log" entry in column 4 and power-function mapping is indicated by a numeric entry, where the number is the exponent in the power function. (A complete description of mapping functions is presented in Wilson *et al.*, 1999a.) The type of rectifier used in the envelope detectors for each subject is indicated in the final column. Additional parameters that were fixed across subjects included 12^{th} order bandpass filters, a 350 to 9500 Hz range of frequencies spanned by the bandpass filters, 4^{th} order lowpass filters, and a "staggered" sequence of electrode stimulation. The bandpass and lowpass filters used an IIR structure and had a Butterworth response. The apical four electrodes in the Ineraid implant were used for subjects SR2 and SR3, and all six electrodes in the implant were used for subjects SR9 and SR10.

Subject	Channels	Mapping	Lowpass Cutoff (Hz)
SR2	4	log	200
SR3	4	log	200
SR9	6	0.1	400
SR10	6	0.1	200

Table 4. Parameters of CIS processors used in the rate/fixed lowpass cutoff series of experiments. The fourth column lists the cutoff frequency of the lowpass filters in the envelope detectors. Additional parameters that were fixed across subjects included fullwave rectifiers in the envelope detectors, 12 μs/phase pulses, 12^{th} order bandpass filters, a 350 to 9500 Hz range of frequencies spanned by the bandpass filters, 4^{th} order lowpass filters, and a "staggered" sequence of electrode stimulation. The bandpass and lowpass filters used an IIR structure and had a Butterworth response. The apical four electrodes in the Ineraid implant were used for subjects SR2 and SR3, and all six electrodes in the implant were used for subjects SR9 and SR10.

eliciting auditory percepts. Parasitic shunting was greatly reduced in the new equipment with the use of driven shields.

Tests. All multichannel processors were evaluated with tests of consonant identification, with each of the consonants presented in an /a/-consonant-/a/ context and in randomized orders. The tokens included multiple exemplars of each consonant from a male talker and, for the experiments involving manipulations in rate with fixed lowpass cutoffs, a female talker as well. Twenty four consonants were used in the tests with subjects SR2, SR3 and SR10, and 16 consonants were used in the tests with subject SR9. The higher number of consonants were used for the first three subjects to bring their 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.

Tests for some experiments also included recognition of monosyllabic words and recognition of key words in sentences. Recognition of monosyllabic words was assessed with presentation of lists from either the Northwestern University Auditory Test 6 (NU6) or the Consonant-Nucleus-Consonant (CNC) test. Recognition of key words in sentences was assessed using lists from the City University of New York (CUNY) test. A separate list was used in the monosyllabic word test for each condition, and four separate lists were used in the sentence test for each condition. Lists were not repeated for any of the subjects. All tests were conducted with hearing alone, and no feedback was given as to correct or incorrect responses.

Results

Manipulations in rate and lowpass cutoff. Effects of manipulations in rate and in lowpass cutoff were measured for all four subjects with tests of consonant identification using the male talker. Contour plots of the percent-correct scores are presented in Figs. 1-3. Figure 1 shows the results with rate and lowpass cutoff axes that cover the ranges used in the tests for each of the subjects. The ranges included rates from 100 to 500 pulses/s/channel, and cutoff frequencies from 12.5 to 500 Hz, for all subjects. Rates for all subjects also included either higher or lower rates or both. In addition, lowpass cutoffs included higher frequencies for three of the subjects.

The raw percent-correct scores underlying the three-dimensional plots of Fig. 1 are presented in Appendix Figs. A.1-4, for each of the subjects respectively. The standard errors of the means for these scores also are presented in Figs. A.1-4.

Figure 2 presents the same data presented in Fig. 1, but with common axes. Note that coverage of the parametric space was greatest for SR2 and least for SR3. Additional conditions were sparsely sampled in the tests with SR3, and results for those conditions are presented in Appendix Fig. A.2 but not in Figs. 1 and 2.

Figure 3 shows results for the combinations of relatively low rates and relatively low cutoff frequencies tested with all subjects. The axes again are the same for all panels in this figure, but with lower rates and lower cutoffs than in Fig. 2.

The plots in Figs. 1-3 show interpolated contours over all possible combinations of rates and cutoff frequencies within the ranges noted above. However, combinations with cutoff frequencies above the rate of stimulation were not tested for subjects SR2, SR3 and SR9, and cutoffs above ½ the rate of stimulation were not tested for subject SR10. Thus, the rightmost corner in each of the contour plots should be interpreted with great caution, as the points in these corners are relatively far from the nearest points in the underlying data.

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

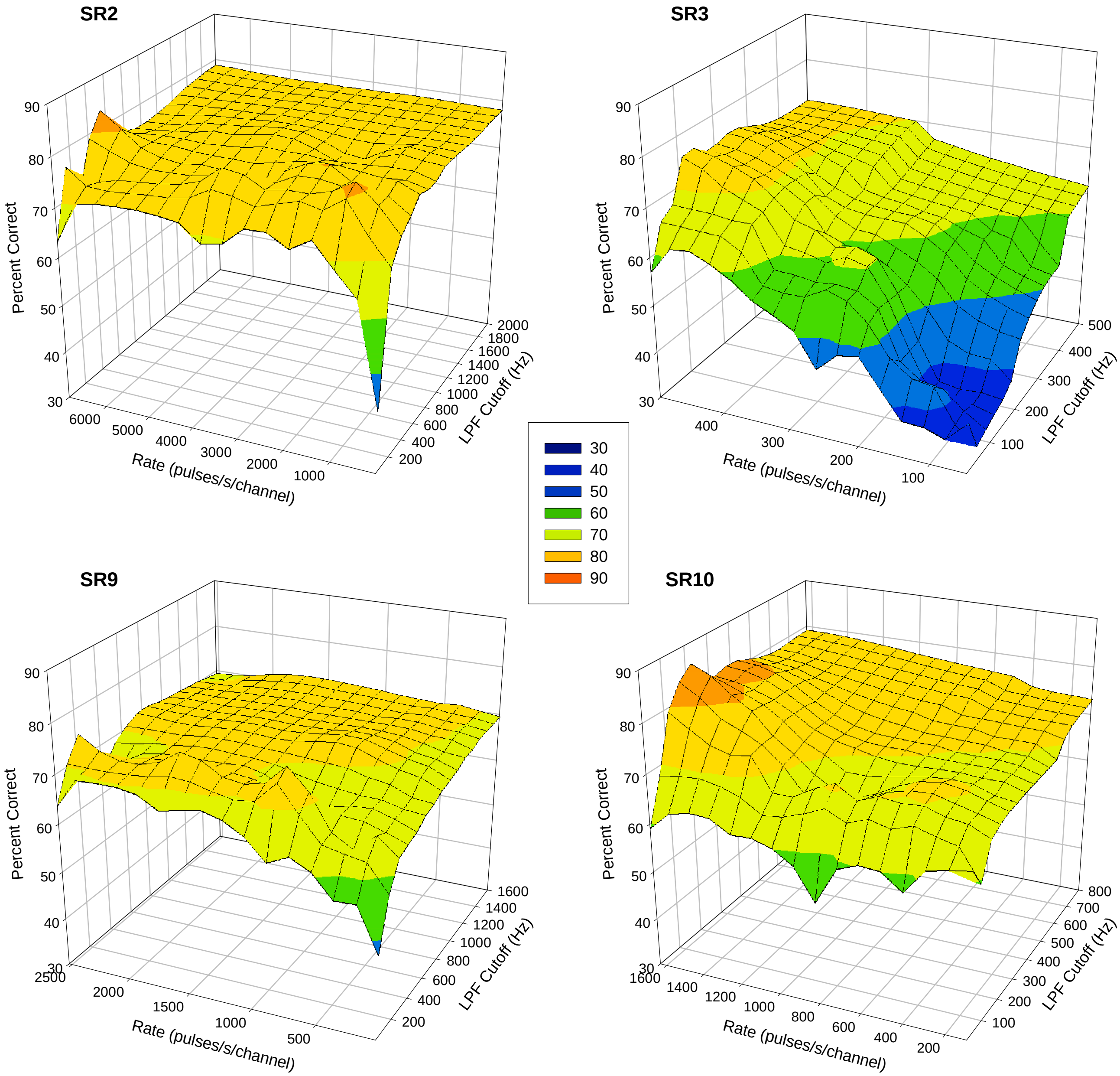

Fig. 1. Consonant identification, male talker. Data for subjects SR2, SR3 and SR10 are from the 24 consonant test, and data for subject SR9 are from the 16 consonant test. Percent correct scores underlying these interpolated, three-dimensional plots are presented in Appendix Figs. A.1-4. Note that the ranges of rates and lowpass filter (LPF) cutoffs vary among subjects.

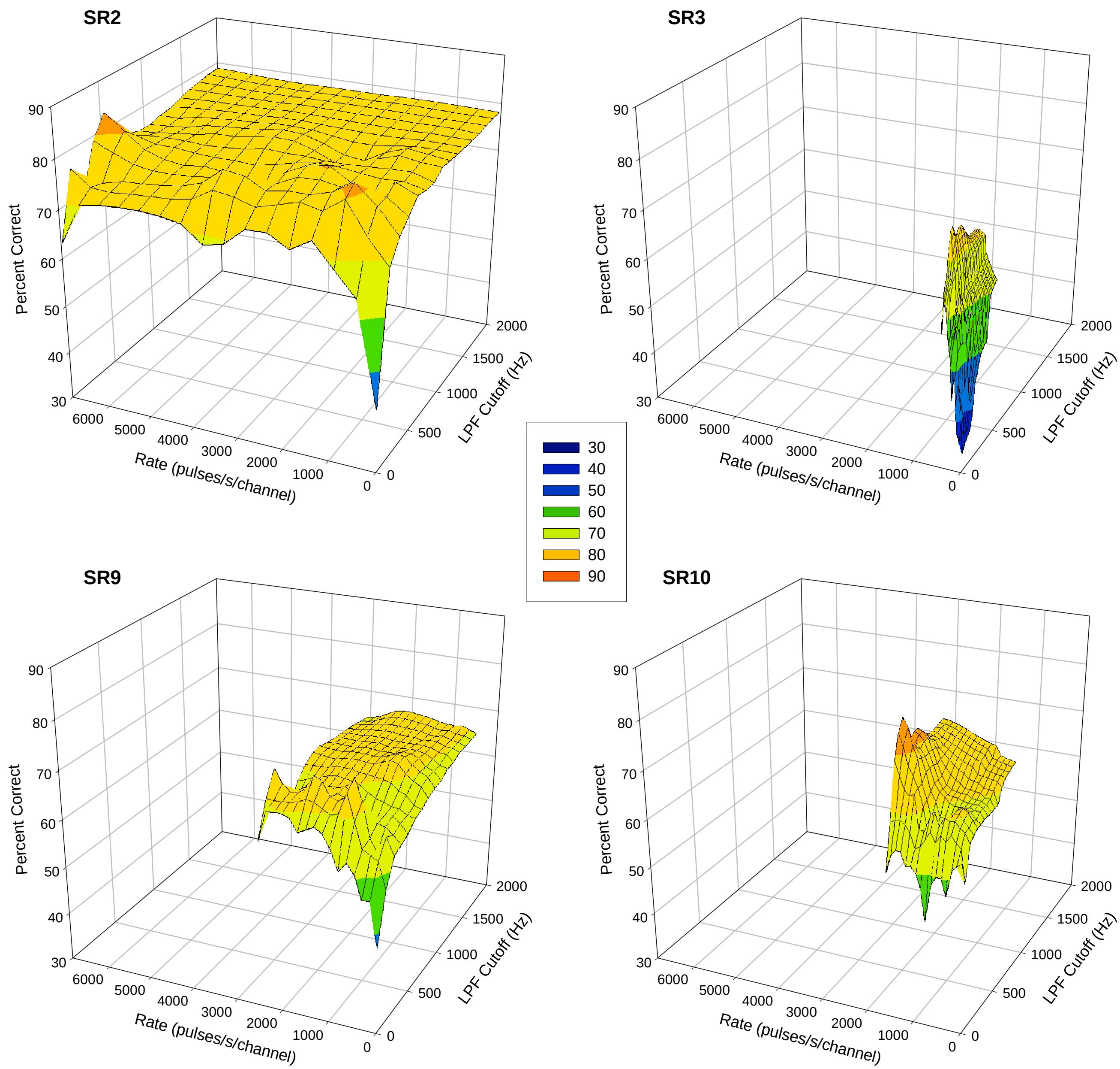

Fig. 2. Consonant identification, male talker, as in Fig. 1, but with common axes for rates and LPF cutoff frequencies.

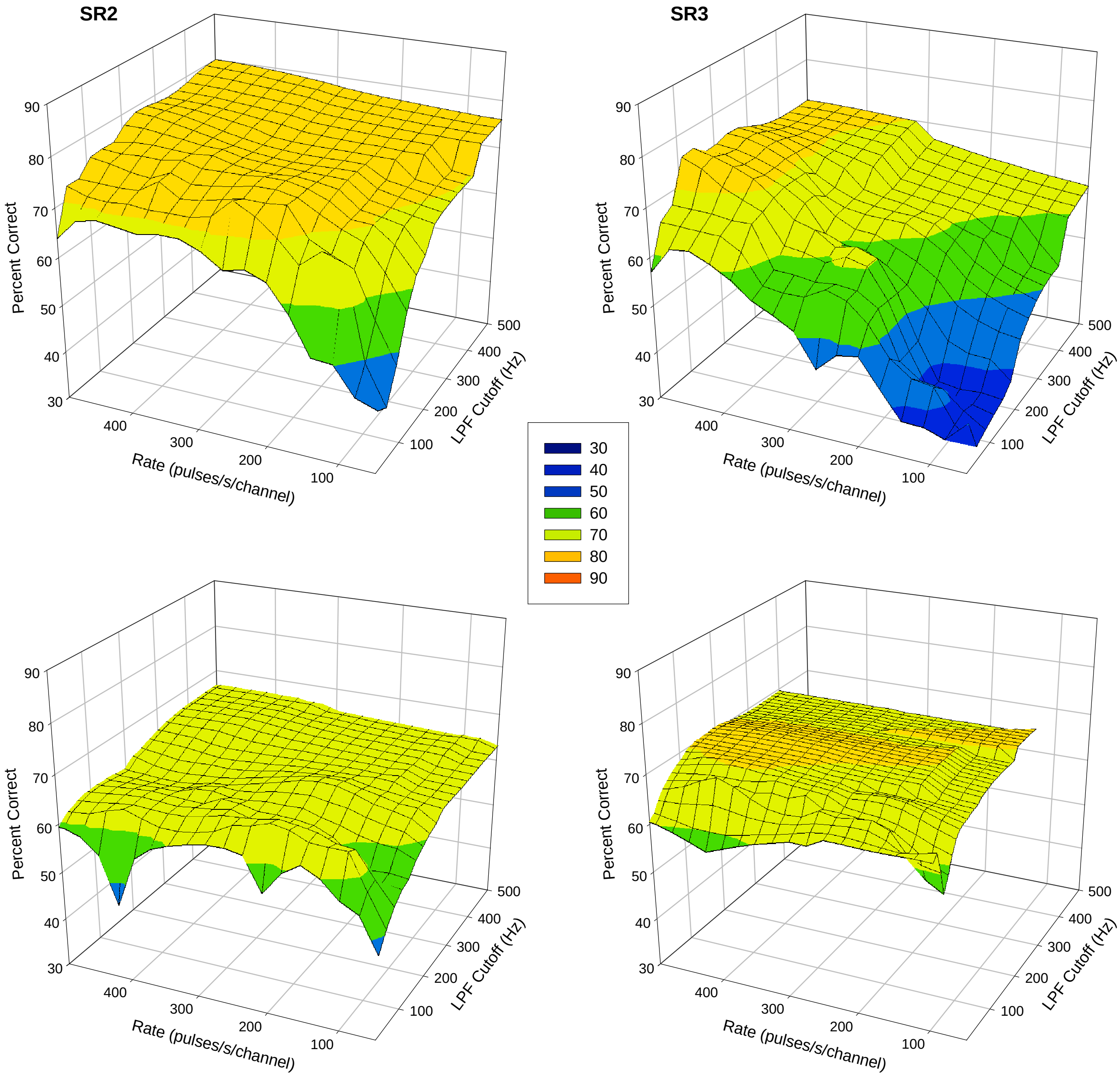

Fig. 3. Consonant identification, male talker, as in Fig. 1, but showing data only for rates at and below 500 pulses/s/channel and for lowpass cutoffs at and below 500 Hz. Data for all subjects include lowpass cutoffs as low as 12.5 Hz. Data for subjects SR2, SR3 and SR9 include rates as low as 50 pulses/s/channel, and data for subject SR10 include rates as low as 100 pulses/s/channel. The data presented in the panel for SR10 include lowpass cutoffs only up to 400 Hz, as the next sample up is at 800 Hz, a relatively large distance from the upper endpoint of the LPF cutoff axis.

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

Lowpass Cutoff (Hz)

Fig. 4. Difference matrix for consonant identification, male talker, subject SR2. This matrix was derived by subtracting the mean of all percent-correct scores for this talker and subject from the score in each cell in the percent-correct matrix presented in Fig. A.1. A one-way analysis of the variance (ANOVA) indicated significant differences among the scores in the matrices of this figure and Fig. A.1. Shaded areas in the difference matrix above indicate scores that are significantly different from the mean according to the Fisher least-significant-difference (LSD) criterion ($p < 0.05$), and 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. Italic type indicates the minimum and maximum values in the matrix. Scores in cells marked with the heavy lines were obtained with 20 blocks of the consonant test, whereas scores in all other cells were obtained with 10 blocks. The Fisher LSD for comparsions between scores in cells with light lines is 6.81; the LSD for comparisons between a score in a cell with light lines versus one in a cell with dark lines is 5.89; and the LSD for comparions between scores in cells with dark lines is 4.81. The Tukey HSD for comparisons between scores in cells with light lines is 13.89; the HSD for comparisons between a score in a cell with light lines versus one in a cell with dark lines is 12.03; and the HSD for comparisons between scores in cells with dark lines is 9.82.

Quantitative comparisons among the scores for each of the subjects are presented in Figs. 4-7. These figures show matrices of the differences in scores between the grand average for all conditions and the score for each tested combination of rate and lowpass cutoff, for each of the subjects.

Rate (pulses/s/channel) \ Lowpass Cutoff (Hz)	12.5	25	50	125	250	500
50	-13.0	***-27.6***	**-20.1**			
125	**-21.3**	-3.4	-8.4	**-18.8**		
250	-13.8	8.7	5.8	9.5	9.1	
500	3.7	**15.4**	12.0	***23.3***	**21.2**	**17.5**

Fig. 5. Difference matrix for consonant identification, male talker, subject SR3. The score in each cell was obtained with 10 blocks of the consonant test. The ANOVA for this matrix (and the associated percent-correct matrix of Fig. A.2) indicated significant differences among the scores. The Fisher LSD for *post hoc* comparisons is 7.69, and the Tukey HSD is 13.81. See the caption to Fig. 4 for a description of how difference matrices are derived and for the meanings of shadings and bold and italic type.

A one-way analysis of the variance (ANOVA) was conducted for each of these matrices and in each case indicated significant differences among the difference scores (or the raw scores, which would produce the same results in a one-way ANOVA). The shaded areas in Figs. 4-7 highlight conditions that produced scores that are significantly different from the grand mean of all scores according the *post-hoc* Fisher least-significant-difference (Fisher LSD) criterion ($p < 0.05$), and the bold type highlights 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 italic 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).

Scores that are significantly below the mean are restricted to low rates and low cutoff frequencies for each of the subjects. Conversely, scores that are significantly above the mean are obtained with higher rates and higher cutoff frequencies. Subject SR2, for instance, scored below the mean for the rate of 50 pulses/s/channel and all tested cutoff frequencies with that rate, and also scored below the mean for the cutoff frequency of 12.5 Hz and most of the tested rates with that cutoff frequency. In addition, he scored below the mean for the rate of 125 pulses/s/channel and the cutoff frequency of 25 Hz. He scored above the mean for most combinations of rate and cutoff frequency at and above 1000 pulses/s/channel and at and above 50 Hz, respectively. He also scored above the mean for the rate of 500 pulses/s/channel and cutoff frequencies at and

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

Fig. 6. Difference matrix for consonant identification, male talker, subject SR9. The ANOVA for this matrix (and the associated percent-correct matrix of Fig. A.3) indicated significant differences among the scores. Scores within the heavy lines were obtained with 20 blocks of the consonant test, whereas scores outside the lines were obtained with 10 blocks. The Fisher LSD for comparsions between scores outside the lines is 9.85; the LSD for comparisons between a score outside the lines versus one inside the lines is 8.53; and the LSD for comparions between scores within the lines is 6.97. The Tukey HSD for comparisons between scores outside the lines is 19.69; the HSD for comparisons between a score outside the lines versus one inside the lines is 17.05; and the HSD for comparisons between scores within the lines is 13.92. See the caption to Fig. 4 for a description of how difference matrices are derived and for the meanings of shadings and bold and italic type.

above 250 Hz. He obtained his highest score at the highest tested rate (6900 pulses/s/channel) and the cutoff frequency of 500 Hz, and he obtained his lowest score at the lowest tested rate (50 pulses/s/channel) and the cutoff frequency of 25 Hz.

Another view of the results is presented in Figs. 8 and 9, which show slices through the rate/lowpass cutoff data, along rows (Fig. 8) or columns (Fig. 9) in the matrices of percent-correct scores (Figs. A.1-4). Figure 8 shows the dependence of scores on the cutoff frequency of the lowpass filter, with rate of stimulation as the parameter, and Fig. 9 shows the dependence of scores on the rate of stimulation, with the cutoff frequency as the parameter. Standard errors of the means for the scores presented in Figs. 8 and 9 can be found in Figs. A.1-4. Standard errors range between 1.2 and 4.0 percent for subject SR2, between 1.6 and 4.0 percent for subject SR3, between 1.3 and 4.8 percent for subject SR9, and between 1.8 and 4.0 percent for subject SR10. The scores shown in Figs. 8 and 9 for subject SR3 include the scores for the additional conditions tested with her, beyond those presented in Figs. 1-3 and 5.

Rate (pulses/s/channel)							
100	-3.8	-2.5	-12.1				
200			-0.4	1.3			
417	-10.8	-7.5	2.1	2.9	3.8		
833	***-18.3***	-6.3	2.1	5.0	-3.3	2.9	
1634	-8.3	-5.0	-0.4	13.3	***19.6***	**14.2**	11.7
	12.5	25	50	100	200	400	800

Lowpass Cutoff (Hz)

Fig. 7. Difference matrix for consonant identification, male talker, subject SR10. The score in each cell was obtained with 10 blocks of the consonant test. The ANOVA for this matrix (and the associated percent-correct matrix of Fig. A.4) indicated significant differences among the scores. The Fisher LSD for *post hoc* comparisons is 7.59, and the Tukey HSD is 14.12. See the caption to Fig. 4 for a description of how difference matrices are derived and for the meanings of shadings and bold and italic type.

The plots in Fig. 8 indicate a general increase in scores with increases in the cutoff frequency of the lowpass filters. Especially low scores are obtained with combinations of low cutoffs and rates at and below 125 pulses/s/channel. For relatively high rates and some subjects, increases in cutoff frequency up to 100 or 200 Hz produce improvements in consonant identification. Further increases in cutoff frequency do not produce monotonic increases in scores.

The plots in Fig. 9 indicate a general increase in scores with increases in the rate of stimulation. Especially low scores are obtained across rates with the cutoff frequency of 12.5 Hz. The largest increases in scores with increases in rate are observed for relatively low rates and for cutoff frequencies above 12.5 Hz. The range of rates over which large increases in scores are produced varies among subjects. For example, a large increase in scores is produced with an increase in rate from 50 to 100 pulses/s/channel for subject SR2, whereas a series of large increases in scores is produced for each increment in rate from 50 to 500 pulses/s/channel for subject SR3.

In some cases, further increases in rate produce further increases in scores. Subject SR10, for example, obtains his highest scores at the highest tested rate (1634 pulses/s/channel), for cutoff frequencies at and above 100 Hz. Those scores at the highest tested rate are significantly higher than the scores for all lower rates (833 pulses/s/channel and lower).

Effects of manipulations in lowpass cutoffs for rates at and above 200 pulse/s/channel are shown in Fig. 10. The data in this figure were derived by averaging the scores at each tested cutoff frequency for each of the subjects, excluding rates at and below 125 pulses/s/channel, that produced marked decrements in scores compared with the higher rates. The bars show standard

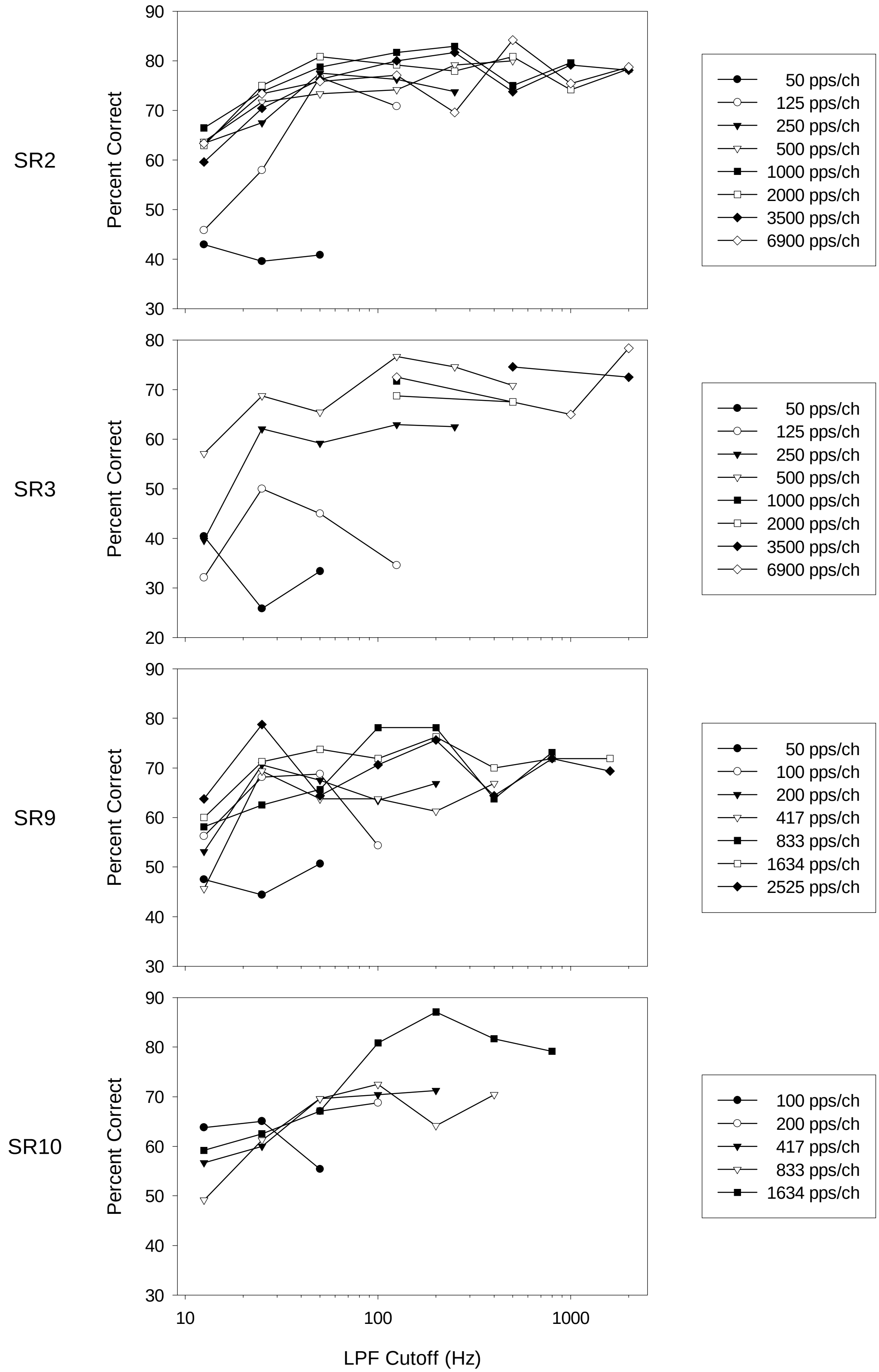

Fig. 8. Slices through the rate/lowpass cutoff data, along rows in the rate/lowpass cutoff matrices. The slices show effects of manipulations in the cutoff frequency of the lowpass filters. Data are from tests of consonant identification in quiet, using the male talker.

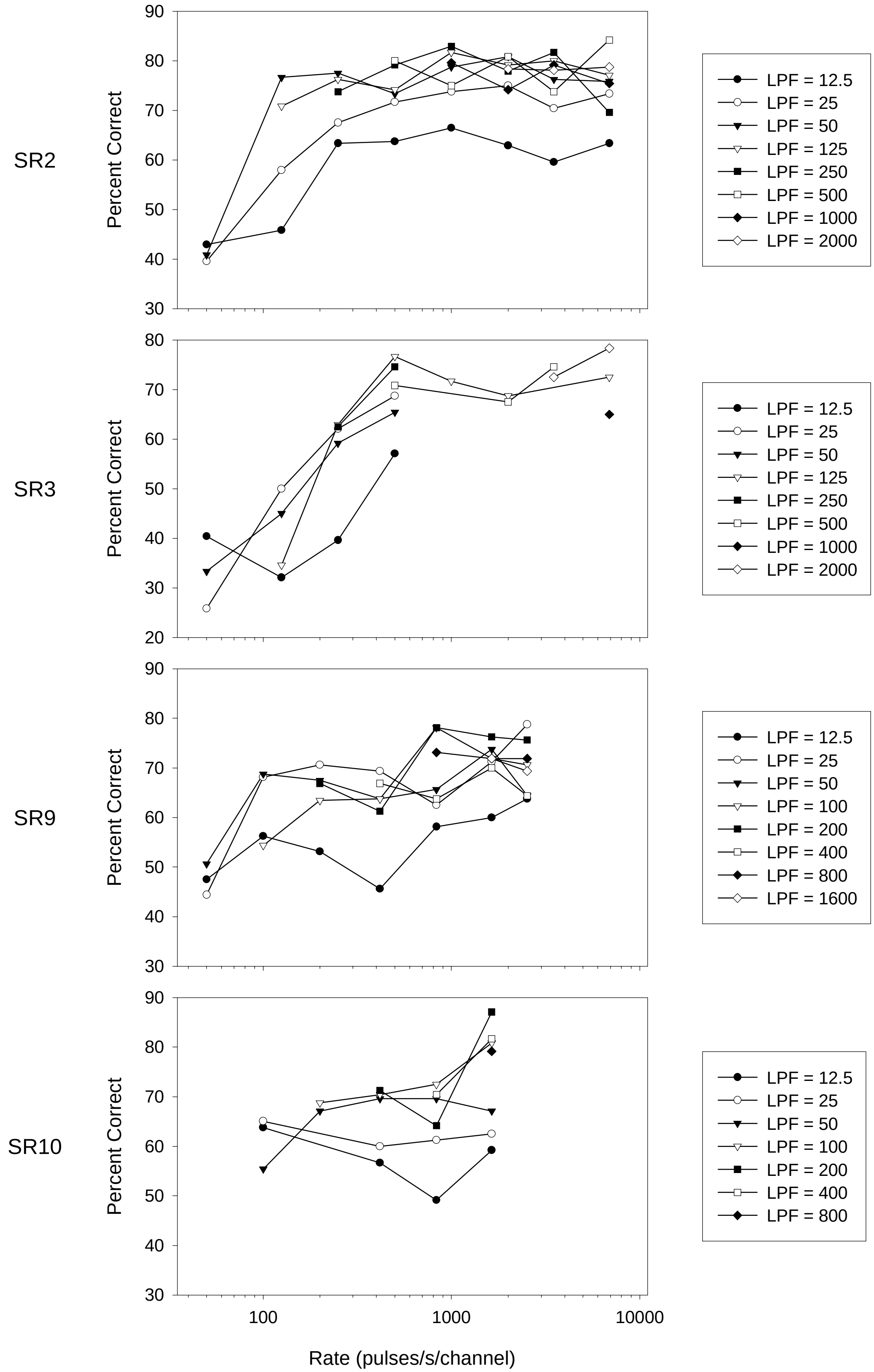

Fig. 9. Slices through the rate/lowpass cutoff data, along columns in the rate/lowpass cutoff matrices. The slices show effects of manipulations in rate of stimulation. Data are from tests of consonant identification in quiet, using the male talker.

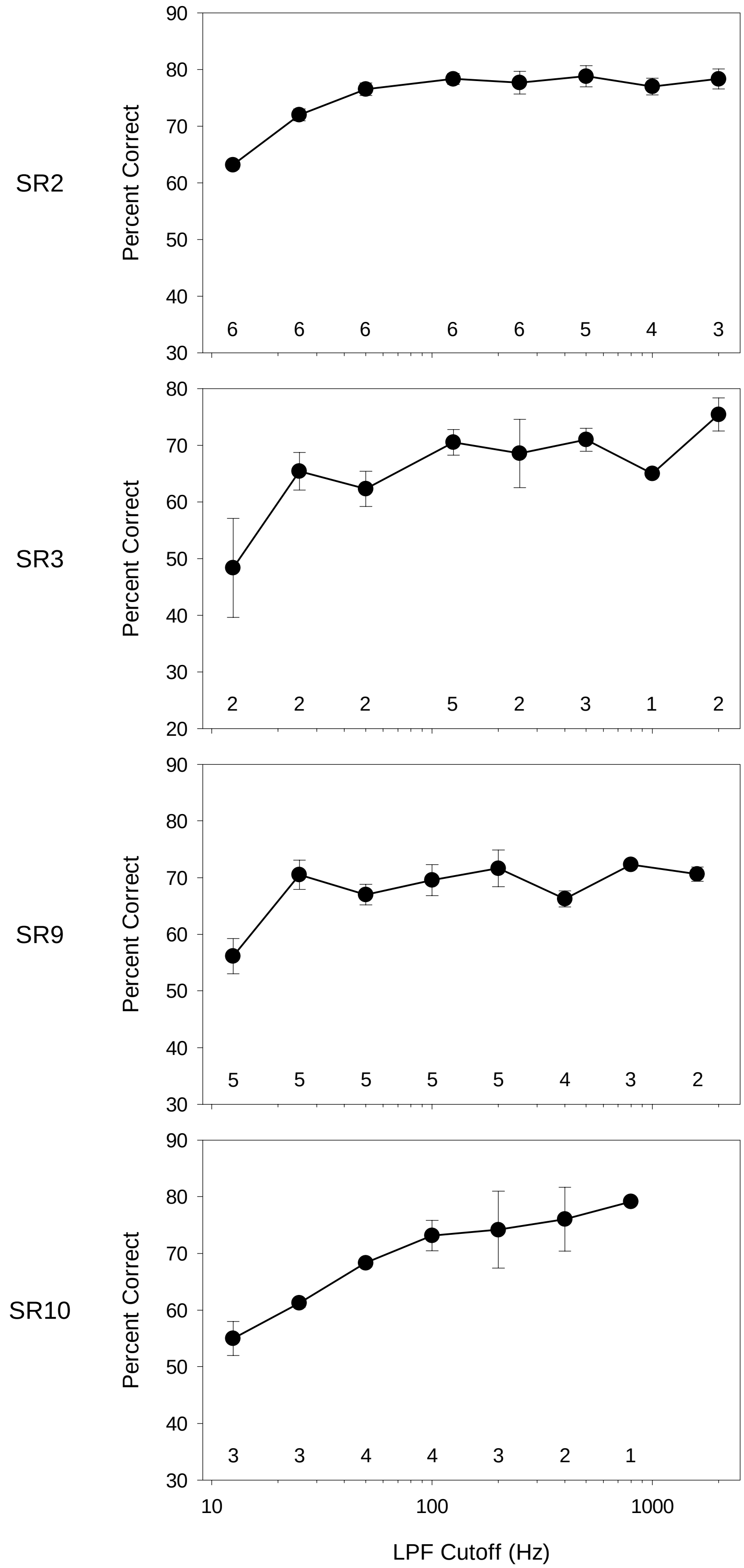

Fig. 10. Means and standard errors of the data presented in Fig. 8, for rates of stimulation at and above 200 pulses/s/channel. The numbers at the bottom of each panel refer to the number of scores averaged for each cutoff frequency.

Subject	Significant differences
SR2	50, 125, 250, 500, 1000, 2000 > 12.5, 25 25 > 12.5
SR3	25, 50, 125, 250, 500, 1000, 2000 > 12.5
SR9	25, 50, 100, 200, 400, 800, 1600 > 12.5
SR10	100, 200, 400, 800 > 12.5, 25 50 > 12.5

Table 5. Significant differences among lowpass cutoff conditions for the data presented in Fig. 10. The differences indicated are those identified by the Fisher LSD criterion ($p < 0.05$). Entries in the table correspond to processors using the indicated cutoff frequencies for the lowpass filters in the envelope detectors (in Hz).

errors of the means for each of the cutoff frequencies. The numbers at the bottom of each panel indicate the number of scores averaged for each cutoff frequency.

A one-way ANOVA was conducted for the data in each of the panels in Fig. 10. Each ANOVA indicated significant differences among the means. The results from *post-hoc* Fisher LSD tests are presented in Table 5.

Figure 10 and Table 5 indicate significant increases in scores with increases in cutoff frequency up to 50 Hz for subject SR2, up to 25 Hz for subjects SR3 and SR9, and up to 100 Hz for subject SR10. Further increases in cutoff frequency do not produce further significant increases in scores for any of the subjects.

Effects of manipulations in rate of stimulation, for cutoff frequencies at and above 25 Hz, are shown in Fig. 11. The data in this figure were derived by averaging the scores at each tested rate for each of the subjects, excluding the cutoff frequency of 12.5 Hz, that produced marked decrements in scores compared with higher cutoff frequencies. As in Fig. 10, the bars show standard errors of the means and the numbers at the bottom of each panel indicate the number of scores averaged for each rate.

As with Fig. 10, a one-way ANOVA was conducted for the data in each of the panels in Fig. 11. The ANOVAs indicated significant differences among the means for subjects SR2, SR3 and SR9 (top three panels) but not for subject SR10 (bottom panel). The results from *post-hoc* Fisher LSD tests are presented in Table 6 for subjects SR2, SR3 and SR9.

Figure 11 and Table 6 indicate significant increases in scores with increases in rate up to 500 pulses/s/channel for subjects SR2 and SR3, and up to 100 pulses/s/channel for subject SR9. The results also indicate a further significant increase in scores with an increase in rate to 1634 pulses/s/channel for subject SR9.

The ANOVA for subject SR10 is not significant. However, as noted before, scores for the rate of 1634 pulses/s/channel are significantly higher than the scores for lower rates, for cutoff frequencies at and above 100 Hz. When the scores for cutoffs at and above 25 Hz are averaged,

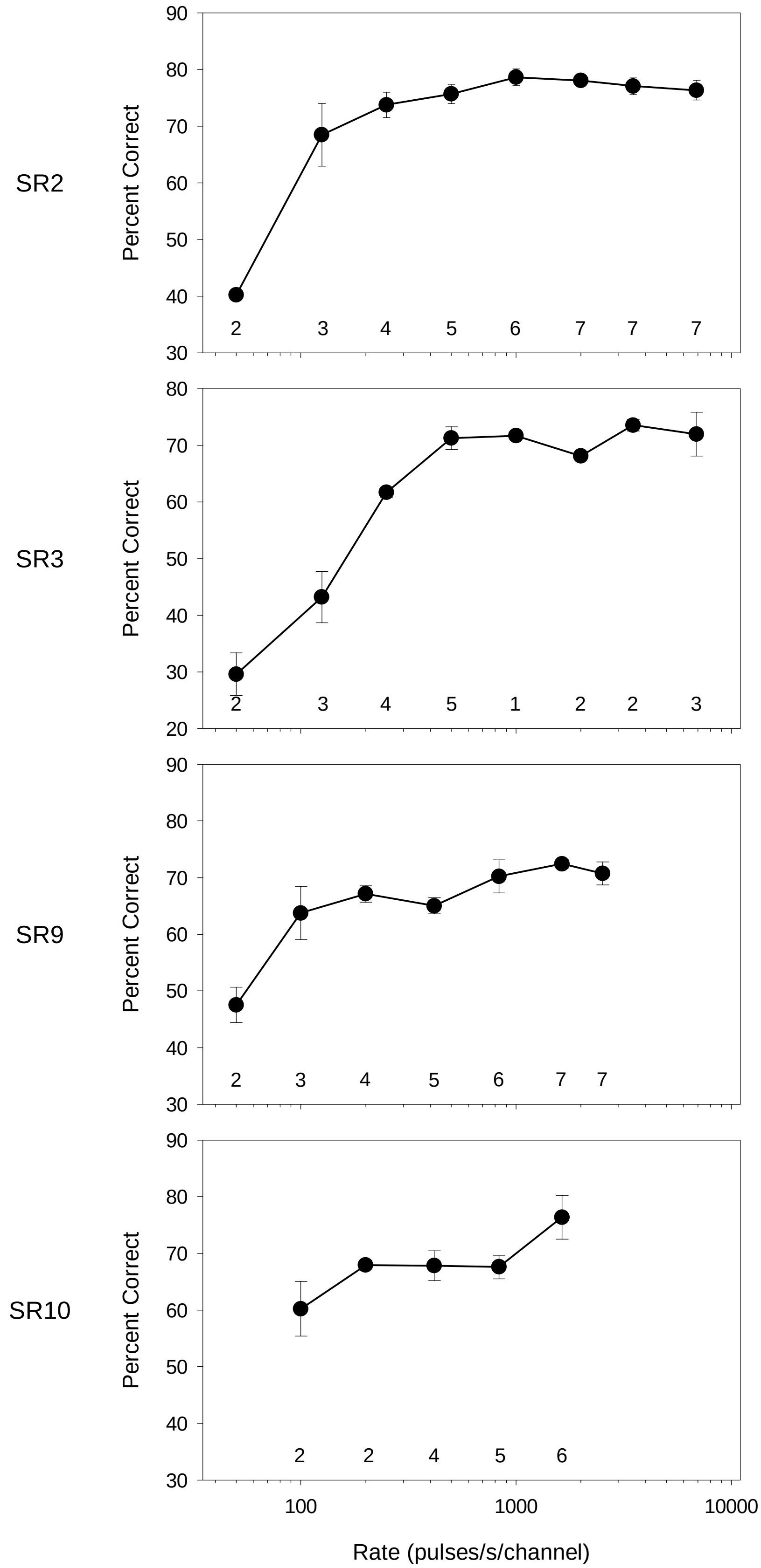

Fig. 11. Means and standard errors of the data presented in Fig. 9, for lowpass cutoff frequencies at and above 25 Hz. The numbers at the bottom of each panel refer to the number of scores averaged for each rate of stimulation.

Subject	Significant differences
SR2	500, 1000, 2000, 3500, 6900 > 50, 125 125, 250 > 50
SR3	3500, 6900 > 50, 125, 250 250, 500, 1000, 2000 > 50, 125 125 > 50
SR9	1634 > 50, 100, 417 100, 200, 417, 833, 2525 > 50

Table 6. Significant differences among pulse rate conditions for the data presented in Fig. 11. The differences indicated are those identified by the Fisher LSD criterion ($p < 0.05$). Entries in the table correspond to processors using the indicated rates of stimulation (in pulses/s/channel).

as in Fig. 11, the differences between the score for the rate of 1634 pulses/s/channel and the scores for the other rates are no longer significant (ANOVA $p = 0.083$).

Feature transmission scores for the consonant tests included in Figs. 10 and 11 are shown in Figs. 12 and 13, respectively. Scores for the transmission of voicing, manner and place information are presented.

One-way ANOVAs were conducted for each feature in each panel of Figs. 12 and 13. The ANOVAs were significant for all cases in Fig. 12 except for voicing for subjects SR3, SR9 and SR10, and except for manner for subject SR9. The ANOVAs were significant for all cases in Fig. 13 except for voicing and manner for subject SR10.

The results from *post hoc* tests (using the Fisher LSD) for the cases in which the ANOVA was significant are presented in Tables 7 and 8, for the conditions of Figs. 12 and 13, respectively. For the conditions of Fig. 12, manipulations in lowpass cutoff frequency affected the transmission of place information more than the transmission of manner or (especially) voicing information. The transmission of voicing information was not affected for three of the subjects by increases in lowpass cutoff over the tested range, from 12.5 to 800 Hz or higher. For subject SR2, increases in the lowpass cutoff from 12.5 to 50 Hz produced increases in the transmission of voicing information, but an increase from 500 to 1000 Hz also produced a decrement in the score for this feature.

Scores for the transmission of manner information improved with increases in the lowpass cutoff from 12.5 Hz to 50 Hz for subjects SR2 and SR10, and from 12.5 Hz to 25 Hz for subject SR3. Manipulations in lowpass cutoff did not affect the transmission of manner information for subject SR9, at least over the tested range of cutoffs for that subject.

Scores for the transmission of place information closely paralleled the percent-correct scores (shown in Fig. 10) for each of the subjects, as a function of lowpass cutoff frequency. The scores for place improved with increases in the lowpass cutoff up to 50, 125, 25 and 50 Hz for subjects SR2, SR3, SR9 and SR10, respectively.

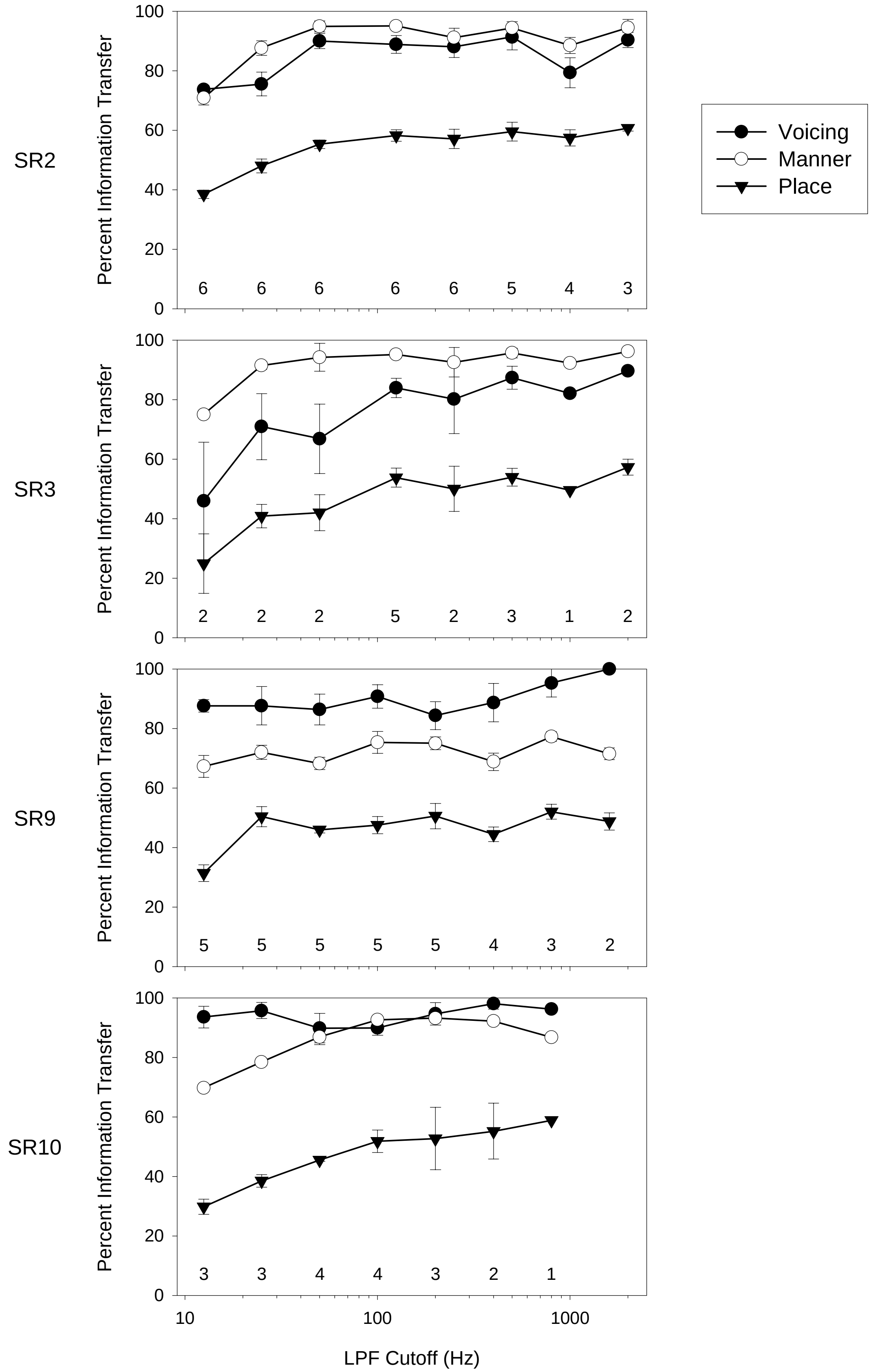

Fig. 12. Feature transmission scores, for the conditions in Fig. 8, that include rates of stimulation at and above 200 pulses/s/channel. The numbers at the bottom of each panel refer to the number of scores averaged for each cutoff frequency. The bars show standard errors of the means.

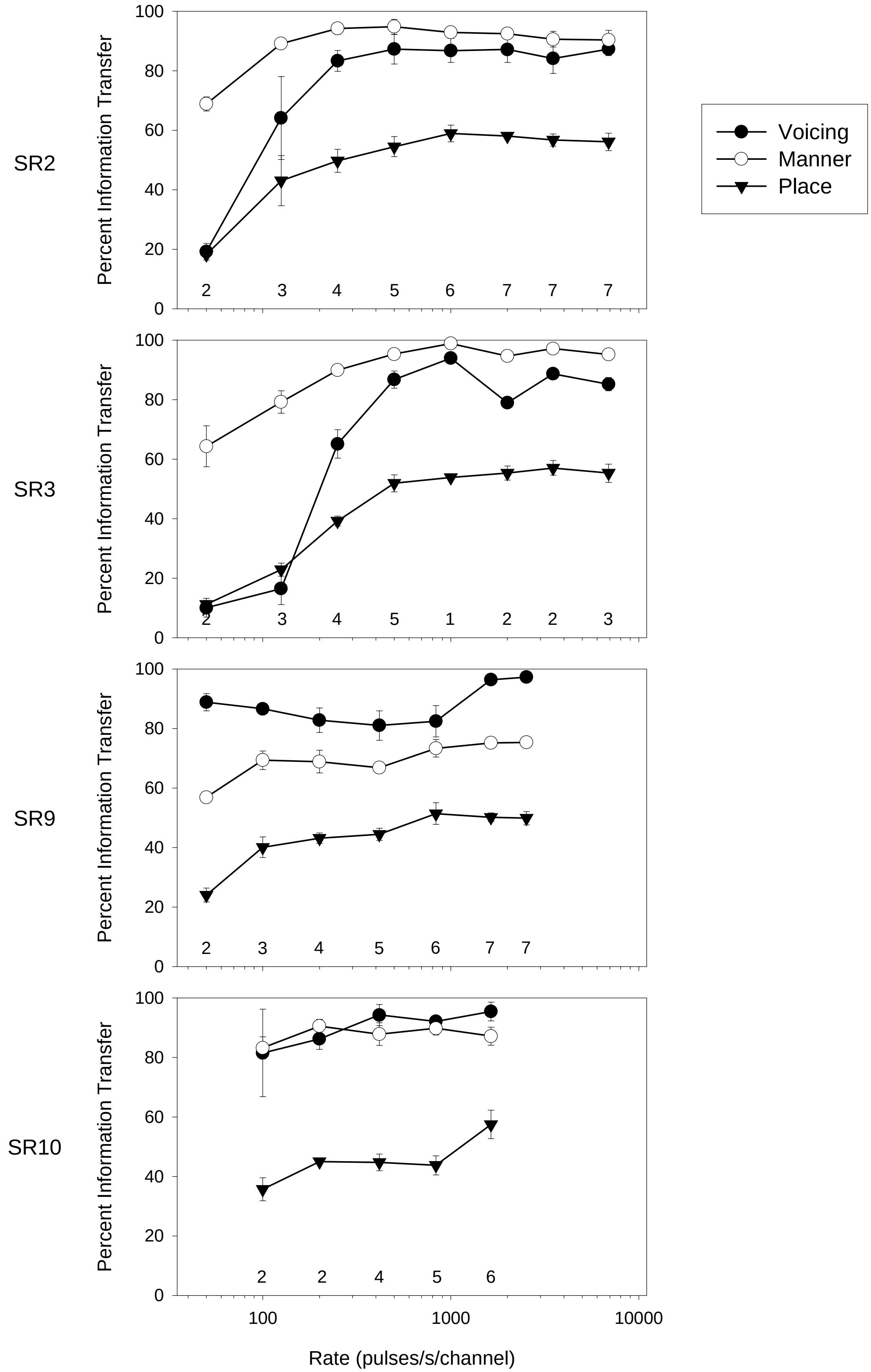

Fig. 13. Feature transmission scores, for the conditions in Fig. 9, that include lowpass cutoff frequencies at and above 25 Hz. The numbers at the bottom of each panel refer to the number of scores averaged for each rate of stimulation. The bars show standard errors of the means.

Subject	**Voicing**	**Manner**	**Place**
SR2	500 > 12.5, 25, 1000 50, 125, 250, 2000 > 12.5, 25	50, 125 > 12.5, 25 25, 250, 500, 1000, 2000 > 12.5	50, 125, 250, 500, 1000, 2000 > 12.5, 25 25 > 12.5
SR3	ANOVA NS	25, 50, 125, 250, 500, 1000, 2000 > 12.5	125, 250, 500, 1000, 2000 > 12.5
SR9	ANOVA NS	ANOVA NS	25, 50, 100, 200, 400, 800, 1600 > 12.5
SR10	ANOVA NS	50, 100, 200, 400, 800 > 12.5, 25 25 > 12.5	50, 100, 200, 400, 800 > 12.5

Table 7. Significant differences among feature transmission scores for the data presented in Fig. 12. The differences indicated are those identified by the Fisher LSD criterion ($p < 0.05$). Entries in the table correspond to processors using the indicated cutoff frequencies for the lowpass filters in the envelope detectors (in Hz).

Subject	**Voicing**	**Manner**	**Place**
SR2	250, 500, 1000, 2000, 3500, 6900 > 50, 125 125 > 50	125, 250, 500, 1000, 2000, 3500, 6900 > 50	500, 1000, 2000, 3500, 6900 > 50, 125 125, 250 > 50
SR3	500, 1000, 2000, 3500, 6900 > 50, 125, 250 250 > 50, 125	250, 500, 1000, 2000, 3500, 6900 > 50, 125 125 > 50	500, 1000, 2000, 3500, 6900 > 50, 125, 250 250 > 50, 125 125 > 50
SR9	1634, 2525 > 200, 417, 833	833, 1634, 2525 > 50, 417 100, 200, 417 > 50	833 > 50, 100, 200 1634, 2525 > 50, 100 100, 200, 417 > 50
SR10	ANOVA NS	ANOVA NS	1634 > 100, 417, 833

Table 8. Significant differences among feature transmission scores for the data presented in Fig. 13. The differences indicated are those identified by the Fisher LSD criterion ($p < 0.05$). Entries in the table correspond to processors using the indicated rates of stimulation (in pulses/s/channel).

For the conditions in Fig. 13, increases in rate of stimulation produced increases in the transmission of place information for each of the subjects. Scores for that feature increased with increases in rate from 50 to 500 pulses/s/channel for subjects SR2 and SR3, from 50 to 833 pulses/s/channel for subject SR9, and from 100 to 1634 pulses/s/channel for subject SR10. Note that the differences in place scores between the highest tested rate for SR10 and lower rates are significant, whereas the differences in percent-correct scores for this subject and these conditions just fail to attain significance.

As with increases in lowpass cutoff frequency, the scores for place closely paralleled the percent-correct scores for increases in rate of stimulation (compare Figs. 11 and 13). Indeed, when plotted on the same scales, the place and percent-correct scores appear to mirror each other almost exactly for all subjects and for manipulations in either rate of stimulation or lowpass cutoff frequency.

Scores for the transmission of voicing information improved with increases in rate of stimulation from 50 to 250 pulses/s/channel for subject SR2, and from 50 to 500 pulses/s/channel for subject SR3. Increases in rate over the tested range did not affect the transmission of voicing information for subject SR10, as mentioned above, and produced a non-monotonic pattern of results for subject SR9, with the highest scores at the two highest tested rates (1634 and 2525 pulses/s/channel) and the lowest scores at intermediate rates (200, 417 and 833 pulses/s/channel).

Scores for the transmission of manner information improved with increases in rate of stimulation from 50 to 125 pulses/s/channel for subject SR2, from 50 to 250 pulses/s/channel for subject SR3, and from 50 to 100 pulses/s/channel for subject SR9. The scores for SR9 also showed another significant increment in manner scores with further increases in rate to 833 pulses/s/channel and higher. As noted before, increases in rate from 100 to 1634 pulses/s/channel did not affect the transmission of manner information for subject SR10.

Single-channel processors. As mentioned in the Background section of this report, increases in rate of stimulation may improve the representation of temporal information within channels, but also may increase undesirable interactions among electrodes (and channels). The undesirable effects may partly offset or even outweigh the desirable effects.

A single-channel variation of CIS processors was tested with subject SR2 to evaluate effects of manipulations in rate and lowpass cutoff frequency in the absence of electrode interactions. In this way, we could assess the effects of the manipulations on the temporal representation only.

The conditions of and results from the tests with single-channel processors are presented in Fig. 14. Rates of stimulation ranged from 833 to 10162 pulses/s, and lowpass cutoff frequencies ranged from 200 to 1600 Hz. The performance for each processor condition was measured with recognition of key words in four lists of the CUNY sentences. Separate sets of lists were used for each of the different conditions.

A one-way ANOVA indicates significant differences among the mean scores for the different conditions. *Post hoc* Fisher LSD tests show that the scores for processors 474, 476 and 478 (see processor designations at the bottom of Fig.14) are significantly higher than the scores for processors 471, 472 and 473, and that the score for processor 475 is significantly higher than the score for processor 473. Each of these significant differences favor processors using the 10162 pulses/s rate, but the differences do not indicate superiority of any one lowpass cutoff condition over another.

Manipulations in rate with fixed lowpass cutoffs. A final set of experiments involved manipulations in rate of stimulation while holding the cutoff for the lowpass filters at a constant (relatively high) frequency for each of the subjects. These experiments included a broad range of speech reception measures.

The results are presented in Figs. 15 and 16. Figure 15 shows results for all four subjects, and Fig. 16 shows results for an additional rate and an additional test included in the measures with subject SR3.

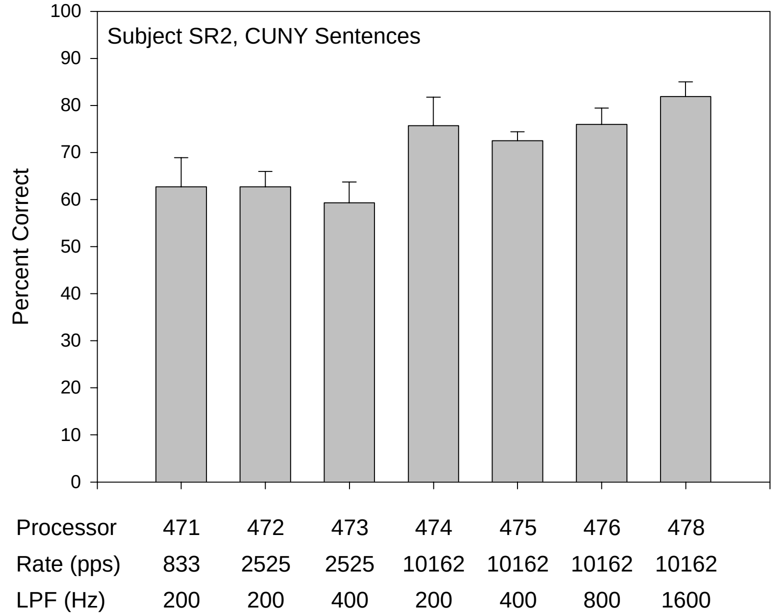

Fig. 14. Recognition of key words in lists of CUNY sentences, subject SR2. A single-channel variation of CIS processors was used for these tests, with the indicated pulse rates and lowpass cutoff frequencies. Stimuli were delivered to electrode 3 in SR2's Ineraid implant, with reference to a remote electrode in the temporalis muscle. The bars show standard errors of the means.

A one-way ANOVA was conducted for the consonant test with the male talker, the consonant test with the female talker, the aggregated results from the consonant tests with each of those talkers, and the CUNY sentence test, for each of the subjects. A one-way ANOVA also was conducted for the additional sentence test included for subject SR3. Results from the tests of monosyllabic word recognition could not be analyzed in this way, in that only a single (separate) list of the words was included for each tested rate for each of the subjects.

The ANOVAs for the subjects, tests and conditions of Fig. 15 indicated significant differences among the scores from the consonant test with the male talker for subjects SR9 and SR10, among the scores from the consonant test with the female talker for subject SR10, and among the scores from the CUNY sentence test for subjects SR2 and SR10. Results from *post hoc* comparisons among scores for these cases are presented in Table 9. In all cases but one the highest or highest two rates produced significantly higher scores than lower rates. The one exception is in the identification of the female consonants by subject SR10. In that case, the two *lowest* rates produced scores that are significantly higher than the score produced by the highest rate. Note that possible differences among scores for the different rates may have been masked by ceiling effects at least for the CUNY tests conducted with subject SR3. The scores for those tests are quite close to 100 percent correct for the rates of 833, 2525 and 5700 pulses/s/channel, and close to 100 percent correct for the rate of 417 pulses/s/channel.

The scores from the monosyllabic word tests are consistent with this general pattern of improvement with the higher or highest rates. Large increases in the scores for these tests are observed with an increase in rate from 417 pulses/s/channel to higher rates for subjects SR2 and SR3, with an increase in rate from 833 to 4000 pulses/s/channel for subject SR9 (the only two tested rates for this subject), and with an increase in rate from 2400 to 4000 pulses/s/channel for subject SR10.

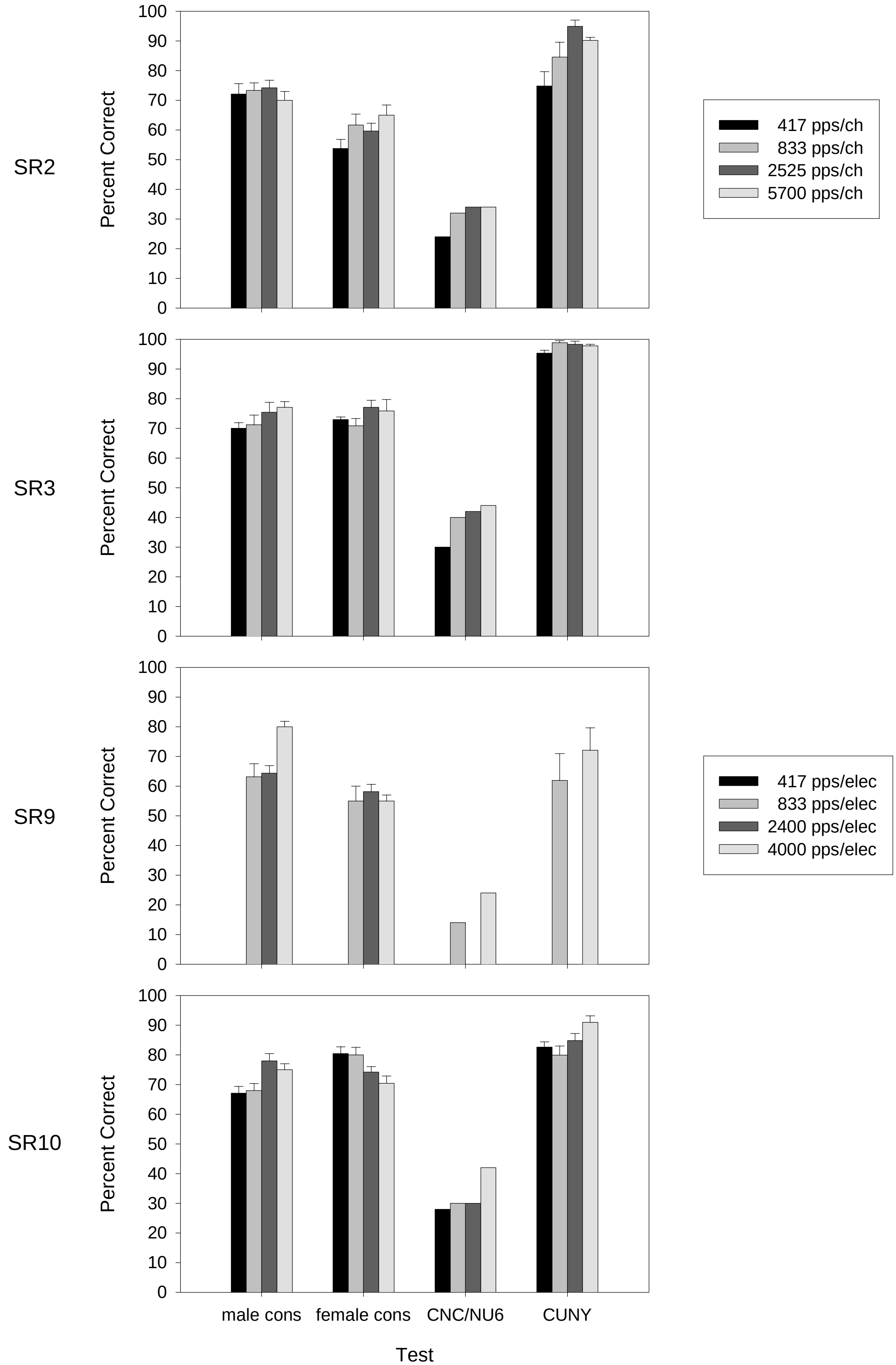

Fig. 15. Effects of rate of stimulation on speech reception. (See full caption on next page.)

Fig. 15. Effects of rate of stimulation on speech reception. Measures included identification of consonants spoken by a male talker and a female talker, recognition of CNC or NU6 monosyllabic words, and recognition of key words in the CUNY sentences. The CNC word test was used for subjects SR2, SR3 and SR10, and the NU6 words were used for subject SR9. Note that not all rates were included in the tests with subject SR9. The bars show standard errors of the means.

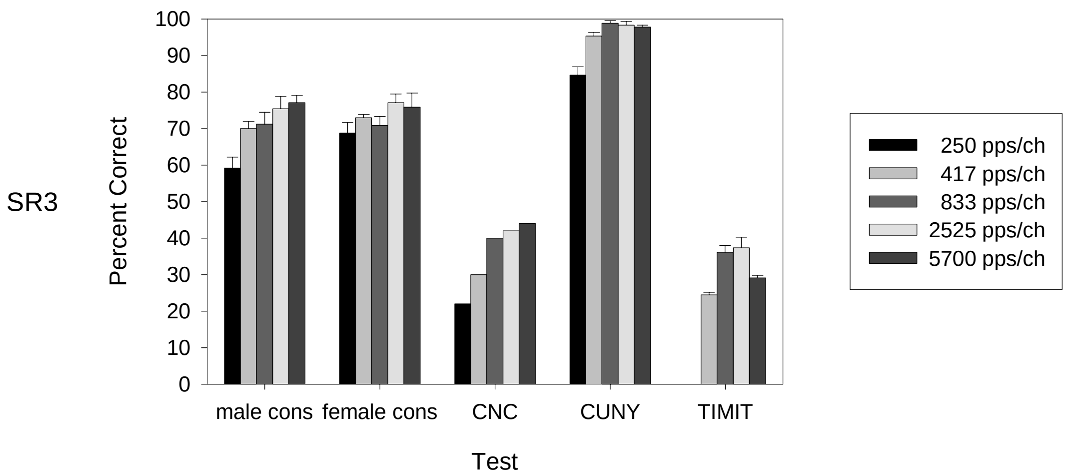

Fig. 16. Chart showing results from an addition rate (250 pulses/s/channel) and an additional test (sentence recognition using the TIMIT speech database, see text) included in the measures with subject SR3. Note that the rate of 250 pulses/s/channel was not included in the tests with the TIMIT sentences.

As mentioned above, results for an additional rate and an additional test included for subject SR3 are presented in Fig. 16. The additional rate is the relatively low rate of 250 pulses/s/channel, and the additional test is one of sentence recognition, using the multiple speakers and relatively difficult material in lists from the Texas Instruments/Massachusetts Institute of Technology (TIMIT) speech database (Garofolo *et al.*, 1993). The rate of 250 pulses/s/channel closely approximates the maximum rate used in the popular *spectral peak* (SPEAK) processing strategy (see Wilson, 2000b, for a description of that and other processing strategies).

One-way ANOVAs for the tests and conditions of Fig. 16 indicate significant differences among the scores for the consonant test with the male talker, the combined consonant tests with both talkers, the CUNY sentence test, and the TIMIT sentence test. *Post hoc* comparisons using the Fisher LSD criterion show that rates at and above 417 pulses/s/channel produce significantly higher scores than the score at 250 pulses/s/channel for the male consonant test, the combined-talkers consonant tests, and the CUNY sentence test. The comparisons for the TIMIT sentence test show that the rates of 833 and 2525 pulses/s/channel produce significantly higher scores than the rates of 417 and 5700 pulses/s/channel.

Subject	Male Cons	Female Cons	M+F Cons	CUNY
SR2	ANOVA NS	ANOVA NS	ANOVA NS	2525, 5700 > 417
SR3	ANOVA NS	ANOVA NS	ANOVA NS	ANOVA NS
SR9	4000 > 833, 2400	ANOVA NS	ANOVA NS	t-test NS
SR10	2400, 4000 > 417, 833	417, 833 > 4000	ANOVA NS	4000 > 417, 833

Table 9. Significant differences in the rate/fixed lowpass filter experiments according to the Fisher LSD criterion. (See Fig. 15 for scores from the experiments.) Entries in the Table correspond to processors using the indicated rates of stimulation (in pulses/s/channel). Speech reception measures included identification of consonants produced by a male talker (Male Cons), identification of consonants produced by a female talker (Female Cons), the combined results from the consonant tests with the male and female talkers (M+F Cons), and recognition of key words in the CUNY sentences (CUNY).

The scores from the monosyllabic word test (CNC words) parallel those from the male consonant test, the combined-talkers consonant tests, and the CUNY sentence test. In particular, scores for the monosyllabic word test increase monotonically with increases in rate of stimulation, with especially large increments in the steps from 250 to 417 pulses/s/channel and from 417 to 833 pulses/s/channel.

Discussion

This study included evaluation of changes in rate of stimulation, and in the cutoff frequency of the lowpass filters used in the envelope detectors of CIS processors, over many combinations of the two parameters. In broad terms, large gains in consonant identification were observed for increases in rate of stimulation from low rates (*e.g.*, 50 pulses/s/channel) to rates up to 100, 500 or 1634 pulses/s/channel depending on the subject. Large gains in performance also were observed for increases in cutoff frequency from 12.5 Hz to 25, 50 or 100 Hz, again depending on the subject. Results for some subjects demonstrated further significant increases in performance with further increases in rate. The highest scores for all four subjects were obtained at the highest tested rate (6900 pulses/s/channel for subjects SR2 and SR3, 2525 pulses/s/channel for subject SR9, and 1634 pulses/s/channel for subject SR10), although these highest scores were not always significantly better than the scores obtained at the lower rates mentioned above. For relatively high rates and some subjects, further increases in cutoff frequency up to 100 or 200 Hz produced improvements in consonant identification. Increases beyond 200 Hz did not produce monotonic increases in scores for any of the subjects.

In the matrix of rate and lowpass conditions for each of the subjects, scores that are significantly below the mean of all scores in the matrix are restricted to low rates and low cutoff frequencies, and scores that are significantly above the mean are restricted to high rates and high cutoff frequencies. Most (but not all) of the improvements in consonant identification are observed for increases in rate up to 500 pulses/s/channel and increases in lowpass cutoff up to 100 Hz. Further significant improvements are observed for some subjects with further increases in rate or with further increases in lowpass cutoff, as also noted above.

We did not observe any consistent interaction between manipulations in rate and manipulations in lowpass cutoff. In general, scores increased rapidly up to a particular rate and up to a particular lowpass cutoff for each of the subjects. For some subjects, a small further increase in lowpass cutoff produced an increase in scores, in conjunction with relatively high rates. These increases were not observed for all subjects, however.

Differences in access to within-channel frequency information among the subjects did not seem to affect the present results. The subjects showed a wide range of abilities in perceiving differences in modulation frequencies as differences in pitch, and yet none of the subjects benefited from increases in lowpass cutoff frequencies beyond 200 Hz. Possibly, although information at frequencies beyond 200 Hz could be perceived by three of the four subjects (see Table 2), the information did not add much for identification of speech sounds.   This idea is consistent with the results from prior studies, which show that most information in speech is contained in frequency variations below 50 Hz (in multiple bands), at least for subjects with normal hearing and for speech presented in quiet conditions.

Increases in lowpass cutoff beyond ¼ or ½ the carrier rate did not produce decrements in consonant identification for the subjects of the present study. The tested combinations of lowpass cutoff and carrier rate included combinations of cutoffs at ¼, ½, and equal to the carrier rate for three of the subjects, and combinations of cutoffs at ¼ and ½ the carrier rate for the remaining subject. One-way repeated-measures (RM) ANOVAs failed to show significant differences among the mean scores for the three combinations for the first three subjects, and a paired-t comparison failed to show a significant difference between the mean scores for the two combinations for the remaining subject.

This finding was somewhat surprising in view of the electrophysiological and psychophysical studies mentioned in the Background section of this report, whose results clearly indicate (1) distortions in the temporal representation of modulation waveforms for modulation frequencies above ¼ the carrier rate and (2) distortions in the perception of modulation frequencies for frequencies above the same limit. Possibly, the most important information for the identification of consonants is in modulation frequencies below 50 Hz, as suggested above and as indicated in results from studies with normal-hearing subjects. If so, inclusion of higher modulation frequencies, through increases in lowpass cutoffs, may not produce a large effect on consonant identification one way or the other, even if the inclusion produces a highly-distorted representation of the higher frequencies in the modulation waveform.

An additional set of experiments in the present study involved manipulations in rate of stimulation, while holding the cutoff frequency at some fixed, relatively-high value for each of the subjects. These experiments included a broad range of speech reception measures. The cutoff frequency was 200 Hz for three of the subjects and 400 Hz for the remaining subject. Rates of stimulation ranged from 417 to 4000 pulses/s/channel or higher for all of the subjects, and included the relatively low rate of 250 pulses/s/channel for one of the subjects.

The results indicated significant differences among speech reception scores for some tests and some subjects, with the above manipulations in rate. In most cases of significant differences, the highest or highest two rates produced higher scores than the lower rates. The rate of 250 pulses/s/channel was markedly inferior to higher rates, for the one subject tested at that lower rate.

In some cases, large increases in speech reception scores were produced with increases in rate above 417 pulses/s/channel. Recognition of the NU6 monosyllabic words was almost doubled, for instance, with an increase in rate from 833 to 4000 pulses/s/channel for subject SR9.

Increases in rate over the studied ranges also produced decrements in performance in exceptional cases. We observed a significant decrement in scores for the identification of female consonants by subject SR10 with an increase in rate from 833 to 4000 pulses/s/channel, and for recognition of key words in TIMIT sentences by subject SR3 with an increase in rate from 2525 to 5700 pulses/s/channel. These exceptions were counterbalanced or outweighed, however, by improvements in the scores from other tests for the same subjects, with increases in rate.

A final set of experiments involved tests with a single-channel variation of CIS processors, in which rate of stimulation and lowpass cutoff frequency were manipulated. Rates ranged from 833 to 10162 pulses/s, and lowpass cutoffs ranged from 200 to 1600 Hz. (The lowpass cutoffs never exceeded ¼ the carrier rate.) The results indicated significant improvements in the recognition of key words in the CUNY sentences with the 10162 pulses/s rate, compared to the other tested rates of 2525 and 833 pulses/s. The average of scores for conditions including the two lower rates was 61.6±2.0 percent correct, and the average of scores for conditions including the highest rate was 76.5±3.9 percent correct. The manipulations in lowpass cutoffs over the tested range did not affect the scores, consistent with the prior findings indicating no significant changes in consonant identification for increases in lowpass cutoff above 200 Hz.

These results from tests with single-channel processors show that large gains in speech reception can be obtained with especially high rates of stimulation, at least in the absence of electrode interactions. The 10162 pulses/s rate is well above the rate at which the auditory nerve responds in a stochastic manner to unmodulated (and presumably modulated) trains of electrical pulses. In contrast, the rates of 833 and 2525 pulses/s are both below the rate at which stochastic effects might be anticipated. Possibly, the highest rate produced stochastic patterns of response in the nerve, and this in turn improved the recognition of speech sounds.

In all of the above experiments, subjects commented that processors using high rates of stimulation sounded more natural and intelligible than processors using lower rates. In the experiments involving extensive manipulations in both rate and lowpass cutoff frequency, subjects also commented that processors with cutoff frequencies of 100 Hz and higher sounded more natural and intelligible than processors with lower cutoff frequencies. Processors with especially low rates (250 pulses/s/channel and lower) produced machine-like percepts, and processors with especially low cutoff frequencies (50 Hz and lower) produced percepts of speech without any inflections and with an unnatural, high-pitched "voice." Combinations of especially low rates and especially low cutoff frequencies produced percepts that were uniformly described as awful by the subjects. (One subject, for example, described processors with these combinations as "the processors from hell.") Thus, although such processors supported relatively high scores in some cases, they were not processors the subjects would like to use in their daily lives.

Results from other studies. Results from other studies, that included manipulations in rate or lowpass cutoff frequency or both, are presented in Figs. 17-24. Conditions and tests for these studies are presented in Table 1.

Data from the study of Brill *et al.*, 1998, are presented in Fig. 17. Scores for individual subjects are shown with the gray symbols and lines in the middle and bottom panels, and the means and standard errors of the means (SEMs) computed from those scores are shown by the black symbols

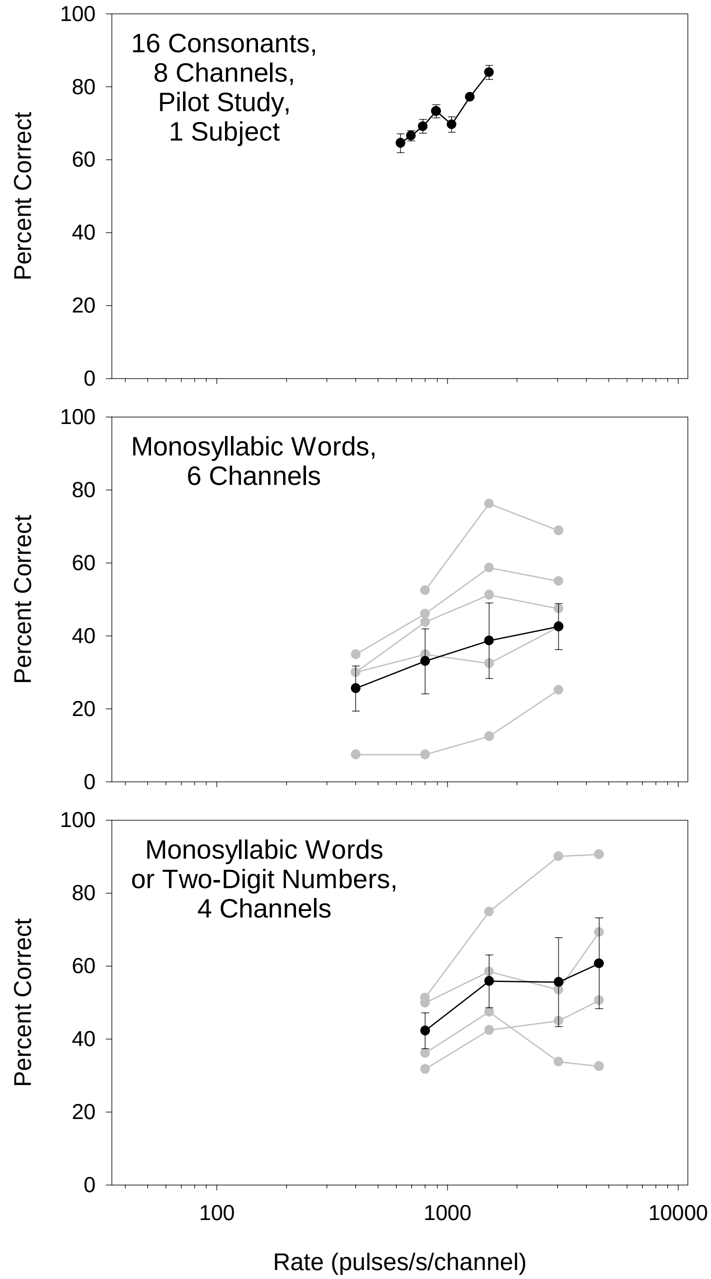

Fig. 17. Data from Brill *et al.*, 1998, showing effects of changes in rate of stimulation. Results from tests with individual subjects are shown with the gray symbols and lines in the bottom two panels, and means and standard errors of the individual scores are shown by the black symbols and lines. Means and SEMs in the middle panel are those for the four subjects tested at all four rates. The subject in the top panel used a COMBI 40 implant system, and the subjects in the middle and bottom panels used COMBI 40+ systems.

and lines. Only one subject was included in the tests of the top panel, and his results are shown with black symbols and lines.

All experiments involved manipulations in rate of stimulation. An eight-channel CIS processor was used for the tests in the top panel, a six-channel processor was used for the tests in the middle panel, and a four-channel processor was used for the tests in the bottom panel. The Med El

COMBI 40 or COMBI 40+ processors used by the subjects could support higher rates of stimulation with smaller numbers of channels.

The mean scores increase monotonically with increases in rate in each of the panels. A one-way ANOVA indicates that the increase is significant for the top panel, and a one-way RM ANOVA indicates that the increase (for the four subjects tested at all four rates) for the middle panel also is significant. A one-way RM ANOVA for the bottom panel indicates that the increase there is not significant.

Post hoc comparisons using the Fisher LSD criterion show that, for the top panel, the highest rate of 1515 pulses/s/channel produced a significantly higher score than the scores for all lower rates, that the rate of 1250 pulses/s/channel produced a significantly higher score than the scores for all lower rates, and that the rate of 893 pulses/s/channel produced a significantly higher score than the scores for the rates of 625 and 694 pulses/s/channel. *Post hoc* comparisons for the middle panel indicate that the highest rate of 3030 pulses/s/channel produced a significantly higher score than the scores for the rates of 400 and 800 pulses/s/channel. The comparisons also indicated that the rate of 1515 pulses/s/channel produced a significantly higher score than the score for the rate of 400 pulses/s/channel.

The gray symbols and lines show a high variability in results among subjects. Three of the five subjects included in the middle panel, for instance, do not show an improvement in scores with the increase in rate from 1515 to 3030 pulses/s/channel, whereas the remaining two subjects show large increases in scores for the same change in rate. One of the subjects exhibits a relatively small gain in speech reception scores over the tested range of rates, while another subject exhibits a more-than-threefold improvement in scores over the range.

Data from the study by Fu and Shannon, 2000, involving manipulations in rate of stimulation over the range from 50 to 500 pulses/s/channel, are presented in Fig. 18. Again, the gray symbols and lines show scores for individuals and the black symbols and lines show means and SEMs for the group. The tests included identification of 12 vowels (top panel), presented in a /h/-vowel-/d/ context, and identification of 16 consonants (middle panel), presented in an /a/-consonant-/a/ context. The bottom panel shows information transmission scores for the consonant features of voicing, manner and place, derived from the aggregated matrix of consonant stimuli and responses for all of the subjects.

One-way RM ANOVAs indicate significant differences among the scores for different rates for both tests. *Post hoc* comparisons using the Fisher LSD criterion show that, for both tests, the scores for rates at and above 150 pulses/s/channel are significantly higher than the scores for the two lower rates (50 and 100 pulses/s/channel). The comparisons also show that the scores at 100 pulses/s/channel are significantly higher than the scores at 50 pulses/s/channel for both tests.

As in the present study, information transmission scores for the place feature are much lower than the scores for voicing and manner. In the study of Fu and Shannon, the scores for manner and place parallel the percent-correct scores, while the scores for voicing continue to increase beyond the rate of 150 pulses/s/channel and up to the tested limit of 500 pulses/s/channel.

Results from the study by Kiefer *et al.*, 2000, are presented in Fig. 19. Eight of the subjects in this study used the COMBI 40 implant and the remaining four subjects used the COMBI 40+ implant. The COMBI 40+ supports higher rates of stimulation than the COMBI 40.

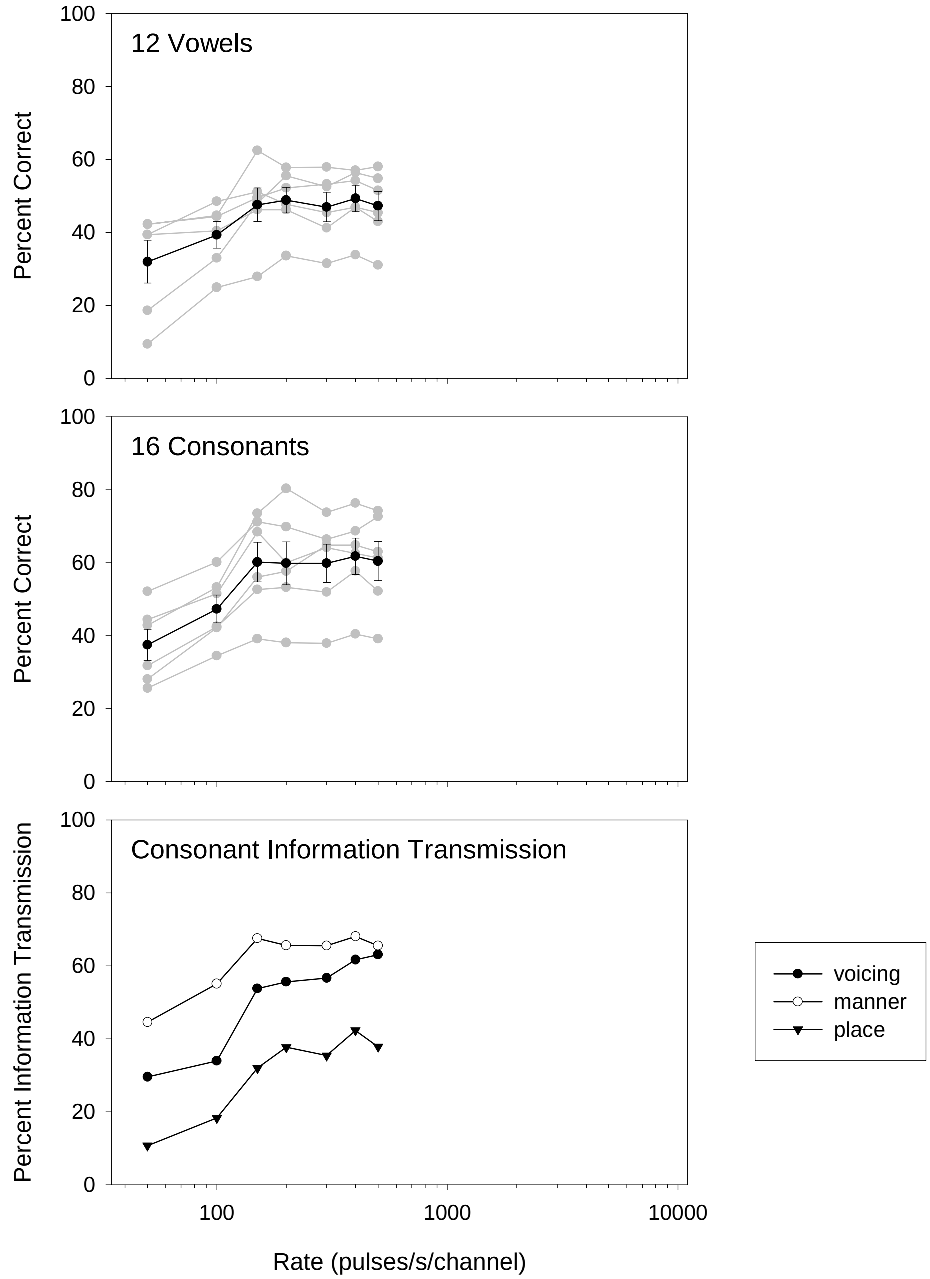

Fig. 18. Data from Fu and Shannon, 2000, showing effects of changes in rate of stimulation. Results from tests with individual subjects are shown with the gray symbols and lines in the upper two panels, and means and standard errors of those scores are shown by the black symbols and lines. The bottom panel shows information transmission scores for the consonant features of voicing, manner and place. The subjects of this study used the Nucleus-22 electrode array in conjunction with a custom speech processor designed to implement a CIS processing strategy.

Fig. 19 shows the data for seven or eight channels of stimulation in the study of Kiefer *et al.* Additional tests were conducted with four channels, and with five or six channels, as indicated in Table 1. Results from those additional tests followed the patterns indicated in Fig. 19, but were somewhat more variable than the results in Fig. 19. All processors in the tests of Fig. 19 used a lowpass cutoff frequency of 400 Hz. (A subsequent set of comparisons between processors using

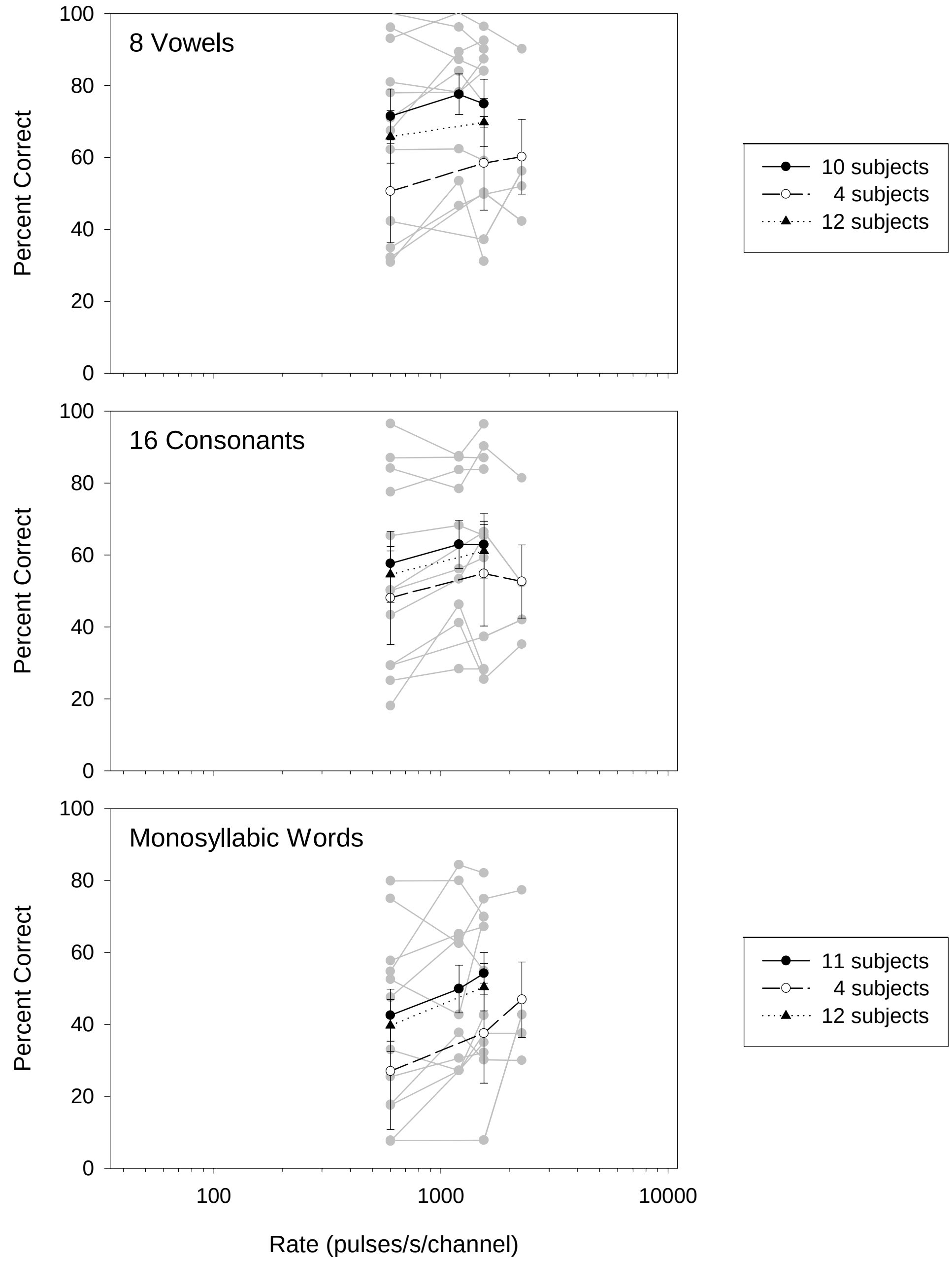

Fig. 19. Data from Kiefer *et al.*, 2000, showing effects of changes in rate of stimulation. Results from tests with individual subjects are shown with the gray symbols and lines, and the means and standard errors of those scores are shown by the black symbols and lines. Three rates of stimulation were used in the tests with most subjects (filled black circles and continuous lines). Four of the subjects were tested with a relatively high rate of stimulation (open black circles and dashed lines), as allowed by their implant device, a COMBI 40+ as opposed to the COMBI 40 used by the other subjects. All of the subjects were tested with two rates of stimulation (filled black triangles and dotted lines).

the rate of 600 pulses/s/channel and cutoffs at 200 versus 400 Hz showed no difference in performance.)

Speech reception measures included identification of 8 German vowels in a /b/-vowel-/b/ context, identification of 16 German consonants in an /a/-consonant-/a/ context, and recognition of monosyllabic words from the lists developed at the University of Freiburg (the "Freiburger words").

As in prior figures, scores for individuals are shown with the gray symbols and lines, and means and SEMs for the group are shown by the black symbols and lines. All twelve subjects were tested at the rate of 600 pulses/s/channel and at the average rate of 1548 pulses/s/channel (this upper rate varied among subjects between 1515 and 1730 pulses/s/channel, depending on the number of channels and implant device). Means and SEMs for them are indicated by the triangles and dotted lines. Ten of the subjects took the vowel and consonant tests using the rates of 600, 1200 and 1548 (average rate) pulses/s/channel (solid circles and continuous lines, top and middle panels). Eleven subjects took the monosyllabic word test using those rates (solid circles and continuous lines, bottom panel). Four of the subjects took each of the tests using the higher rate of 2272 pulses/s/channel, as allowed by their COMBI 40+ implants (open circles and dashed lines, all panels). Additional rates included 600, 1200 and 1548 (average rate) pulses/s/channel for two of those four subjects for the vowel and consonant tests, and for three of the subjects for the monosyllabic word test. The remaining subjects in the group of four were not tested at the rate of 1200 pulses/s/channel.

As can be seen from the gray symbols and lines, the results are highly variable among subjects. Some subjects show monotonic increases in scores with increases in rate, whereas others show large peaks or dips at intermediate rates. A few subjects exhibit spectacular increases in scores with increases in rate, for example, the subject with the lowest trace in the bottom panel of Fig. 19.

One-way RM ANOVAs indicate that the differences in mean scores across rates, for the groups of 10 and 4 subjects taking the vowel and consonant tests, are not significant. Paired t tests show that the mean of scores for all 12 subjects is significantly higher at the (average) rate of 1548 pulses/s/channel than at the rate of 600 pulses/s/channel, for identification of consonants (middle panel) but not for vowels (top panel).

One-way RM ANOVAs for the groups of 11 and 4 subjects taking the monosyllabic word tests indicate significant differences among the mean scores for the different rates for the group of 11 but not for the group of 4. *Post hoc* comparisons for the group of 11, using the Fisher LSD criterion, further show that the mean score for the rate of 1548 pulses/s/channel is significantly higher than the mean score for the rate of 600 pulses/s/channel. A paired-t comparison of mean scores at the two rates included in the tests for all 12 subjects indicates a significant difference in the scores. The score for 1548 pulses/s/channel (50.3±6.6 percent correct) is significantly higher than the score for 600 pulses/s/channel (39.7±7.2 percent correct).

Data from the study by Lawson *et al.*, 1996, are presented in Fig. 20. As in prior figures, scores for individuals are shown with the gray symbols and lines, and group scores are shown by the black symbols and lines. A 24-consonant test was used for two of the five subjects in the study (gray circles), and a 16-consonant test was used for the remaining subjects (gray triangles). Results from consonant tests with a male talker are shown in the figure; results from tests with a female talker were similar to those for the male talker.

A one-way RM ANOVA indicates that the differences in mean scores among the tested rates are not significant. Two of the subjects show increases in scores with increases in rate (two lower traces in Fig. 20), but the group scores are not different across rates.

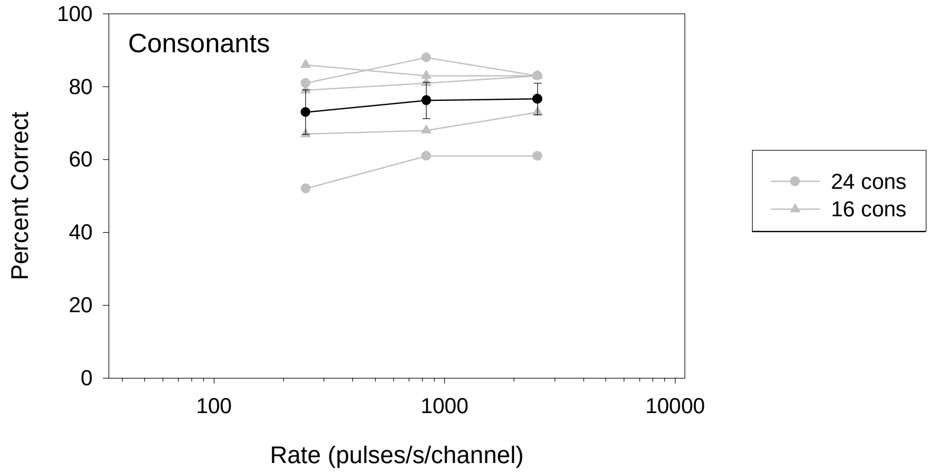

Fig. 20. Data from Lawson *et al.*, 1996, showing effects of changes in rate of stimulation. Results from tests with individual subjects are shown with the gray symbols and lines, and means and standard errors of those scores are shown by the black symbols and lines. A 24-consonsont test was used with two of the subjects (gray circles), and a 16-consonant test was used with the remaining three subjects (gray triangles). The subjects of this study used the Nucleus-22 electrode array in conjunction with a percutaneous connector and a custom speech processor designed to implement a CIS processing strategy.

Results from the study by Loizou and Poroy, 1999, are presented in Fig. 21. The top two panels show results from tests of vowel and consonant identification, respectively, and the bottom panel shows results for recognition of monosyllabic words by the subjects. The third panel down shows information transmission scores for the consonant features of voicing, manner and place. Individual scores for the monosyllabic word tests are shown in the bottom panel with the gray symbols and lines, and the means and SEMs of those scores are shown by the black symbols and lines. Three different vowel contexts were used for the consonant tests, and scores for these different contexts are indicated with the gray symbols and lines in the second panel of the figure. The contexts included a /u/-consonant-/u/ context (gray circles), an /i/-consonant-/i/ context (gray inverted triangles), and an /a/-consonant-/a/ context (gray squares). The grand means from all of these consonant tests are indicated in the same panel by the black symbols and lines.

One-way RM ANOVAs indicate significant differences among the mean scores for the consonant and monosyllabic word tests, but not for the vowel test. *Post hoc* comparisons for the consonant tests indicate that the score for 2100 pulses/s/channel is significantly higher than the scores for 400 and 800 pulses/s/channel, and that the scores for 800 and 1400 pulses/s/channel are significantly higher than the score for 400 pulses/s/channel. *Post hoc* comparisons for the monosyllabic word tests indicate that the scores for 800, 1400 and 2100 pulses/s/channel are significantly higher than the score for 400 pulses/s/channel.

Results for the different vowel contexts used in the consonant tests show monotonic increases in scores with increases in rate for the /u/-consonant-/u/ and /i/-consonant-/i/ contexts, but not for the /a/-consonant-/a/ context. Scores for the /a/-consonant-/a/ context do not increase with increases in rate for rates higher than 800 pulses/s/channel. (This finding suggests that the /a/-consonant-/a/ context used in the present study, and in the studies by Fu and Shannon and by Kiefer *et al.*, may not have been as sensitive as other contexts for demonstrating effects of rate of stimulation on consonant identification.)

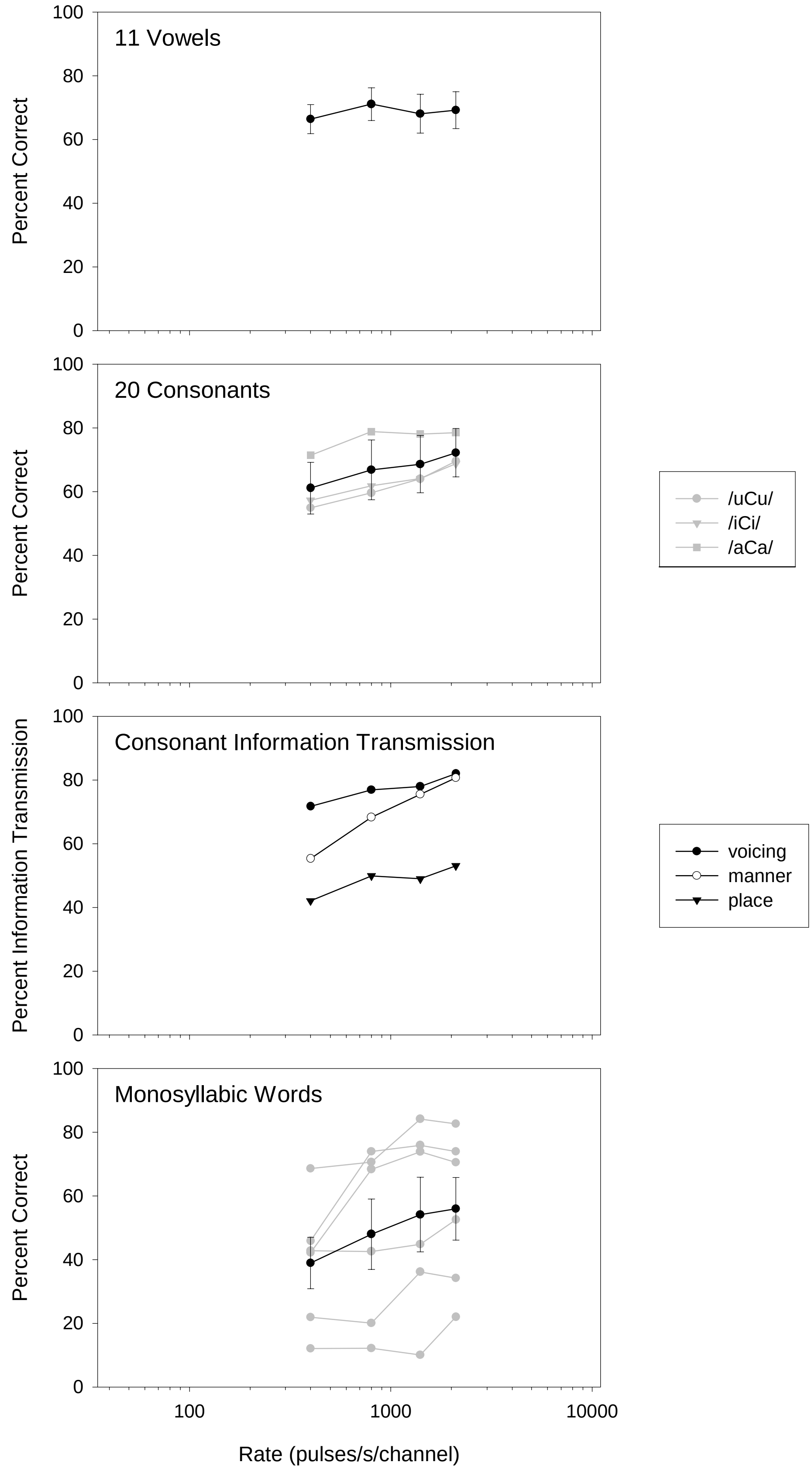

Fig. 21. Data from Loizou and Poroy, 1999. (See full caption on next page.)

Fig. 21. Data from Loizou and Poroy, 1999, showing effects of changes in rate of stimulation. Black symbols with error bars show means and standard errors for identification of vowels, identification of consonants, and recognition of monosyllabic words by six subjects in the top, next to top, and bottom panels, respectively. Results from consonant tests using different vowel contexts are shown in the next-to-the-top panel with gray symbols and lines. Results for individual subjects from the test of word recognition are shown in the bottom panel with the gray symbols and lines. The next-to-the bottom panel shows information transmission scores for the consonant features of voicing, manner and place. The subjects of this study used the Ineraid electrode array in conjunction with and percutaneous connector and a custom speech processor designed to implement a CIS processing strategy.

Scores for the transmission of voicing and place information mirror the percent-correct scores for the consonant tests. Scores for the transmission of manner information show larger increases with increases in rate compared with the other scores just mentioned. A one-way RM ANOVA indicates significant differences in the scores for manner for the different rates, and *post hoc* comparisons further show that the scores for 1400 and 2100 pulses/s/channel are significantly higher than the scores for 400 and 800 pulses/s/channel.

As in the other studies reviewed above, a high variability is observed in the patterns of scores among subjects. The variability in the study by Loizou and Poroy is illustrated in the bottom panel of Fig. 21, which shows individual and group scores for the monosyllabic word tests. Although the scores for all subjects demonstrated improvements with increases in rate, the improvements occurred at different steps in rate for different subjects. None of the subjects showed a continuous set of improvements across each step in rate over the tested range of rates. However, each of the subjects had a much higher score at the highest tested rate (2100 pulses/s/channel) than at the lowest tested rate (400 pulses/s/channel).

Data from the study by Pelizzone *et al.*, 1998, are presented in Fig. 22. This study included a comparison between five-channel processors using a relatively high rate of stimulation (2000 pulses/s/channel) versus otherwise identical processors using a quite high rate of stimulation (20000 pulses/s/channel). The tests included identification of 7 French vowels presented alone without a leading or following consonant and identification of 14 French consonants presented in an /a/-consonant-/a/ context. The investigators did measure some electrical crosstalk among channels and electrodes for the higher rate of stimulation, but noted that the measured levels were below auditory threshold for any one channel. (Aggregate effects of perception through multiple channels were not evaluated.)

Paired t comparisons for each of the tests do not indicate significant differences between the mean scores for the two rates. Among individuals, however, one of the four subjects showed significant improvements in scores for the both the vowel and consonant tests with the increase in rate (bottom gray trace in each panel of Fig. 22). Scores for the other subjects were not significantly different between rates.

Direct electrical crosstalk, in addition to increased levels of non-simultaneous interactions among electrodes and channels, may have counteracted possible improvements in the temporal representation at the higher rate. Also, use of the /a/-consonant-/a/ context may have reduced the sensitivity for demonstration of possible improvements, compared to other contexts.

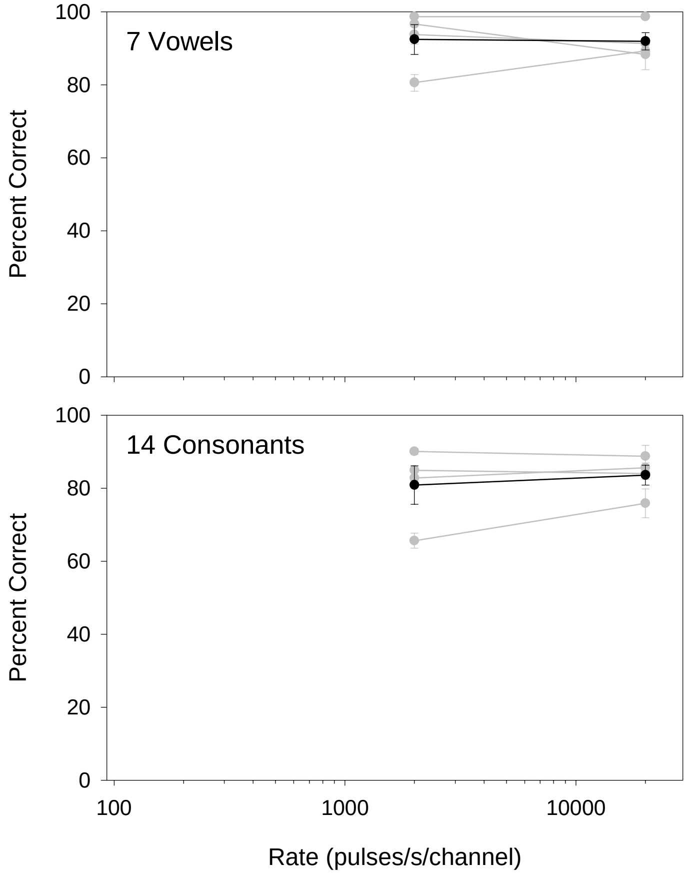

Fig. 22. Data from Pelizzone *et al.*, 1998, showing effects of changes in rate of stimulation. Results from tests with individual subjects are shown with the gray symbols and lines, and means and standard errors of those scores are shown by the black symbols and lines. Note that the rate axis is shifted relative to that of other figures in this report, to show scores for the tested rate of 20000 pulses/s/channel. The subjects of this study used the Ineraid electrode array in conjunction with and percutaneous connector and a custom speech processor designed to implement a CIS processing strategy.

A summary of significant differences in scores among different rates of stimulation, from the various studies described above, is presented in Table 10. All such differences favor higher rates over lower rates. In addition, many of the differences indicate improvements in speech reception performance with increases in rate from rates above 500 pulses/s/channel to higher rates, consistent with the results from the present study.

Results from the present and the reviewed studies show a high variability in scores among subjects, with manipulations in rate. One possible explanation for at least part of this variability is that the scores for each subject reflect a competition between a better representation of envelope signals versus possible increases in electrode interactions, with increases in rate. The relative weights of these two factors may vary among subjects. For example, a subject with high auditory thresholds might be expected to also have relatively high electrode (and channel) interactions for rapidly-presented pulses. Such high interactions may offset, or more than offset, any benefits of high-rate stimulation beyond a certain rate. On the other hand, a subject with low

Study	Subjects	Test	Rates
Brill *et al.*, 1998	1	16 consonants	1515 > 625, 694, 781, 893, 1042, 1250 1250 > 625, 694, 781, 1042 893 > 625, 694
	4	Monosyllabic words	3030 > 400, 800 1515 > 400
Fu & Shannon, 2000	6	12 vowels	150, 200, 300, 400, 500 > 50, 100 100 > 50
		16 consonants	150, 200, 300, 400, 500 > 50, 100 100 > 50
Kiefer *et al.*, 2000	12	16 consonants	1548 (average rate) > 600
	11	Monosyllabic words	1548 (average rate) > 600
	12	Monosyllabic words	1548 (average rate) > 600
Loizou & Poroy, 1999	6	20 consonants	2100 > 400, 800 800, 1400 > 400
		Monosyllabic words	800, 1400, 2100 > 400

Table 10. Significant differences in scores among different rates of stimulation, as reported from various studies. Entries in the rightmost column correspond to processors using the indicated rates of stimulation (in pulses/s/channel).

auditory thresholds and low interactions might enjoy improvements in speech reception over a wide range of increases in rate.

Data from studies that included evaluation of effects of changes in lowpass cutoff frequency are presented in Figs. 23 and 24. Data from the study by Fu and Shannon, 2000, are presented in Fig. 23, and data from the study by Lawson *et al.*, 1996, are presented in Fig. 24.

The study by Fu and Shannon included tests of vowel identification and consonant identification, as noted above (see Fig. 18 and the accompanying description). In the part of the study involving manipulations in lowpass cutoff frequency, each subject used a four-channel processor with a stimulus rate of 500 pulses/s/channel.

One-way RM ANOVAs indicate significant differences among the means for both the vowel and consonant tests, for the lowpass cutoff conditions of Fig. 23. *Post hoc* comparisons using the Fisher LSD criterion further show that, for the vowel tests, the scores for the lowpass cutoffs of 10, 20, 40, 80 and 160 Hz are significantly higher than the score for the cutoff of 2 Hz. The comparisons for the vowel tests also show that the score for the cutoff of 5 Hz is significantly higher than the score for the cutoff of 2 Hz.

Post hoc comparisons for the consonant tests show that the score for the cutoff of 160 Hz is significantly higher than the scores for the cutoffs of 2, 5, 10 and 20 Hz, that the scores for the cutoffs of 20, 40 and 80 Hz are significantly higher than the scores for the cutoffs of 2, 5 and 10 Hz, that the score for the cutoff of 10 Hz is significantly higher than the scores for the cutoffs of 2 and 5 Hz, and that the score for the cutoff of 5 Hz is significantly higher than the score for the cutoff of 2 Hz. These significant differences for the consonant tests indicate improvements in the scores out to the tested limit of 160 Hz, although the magnitude of the overall improvement from

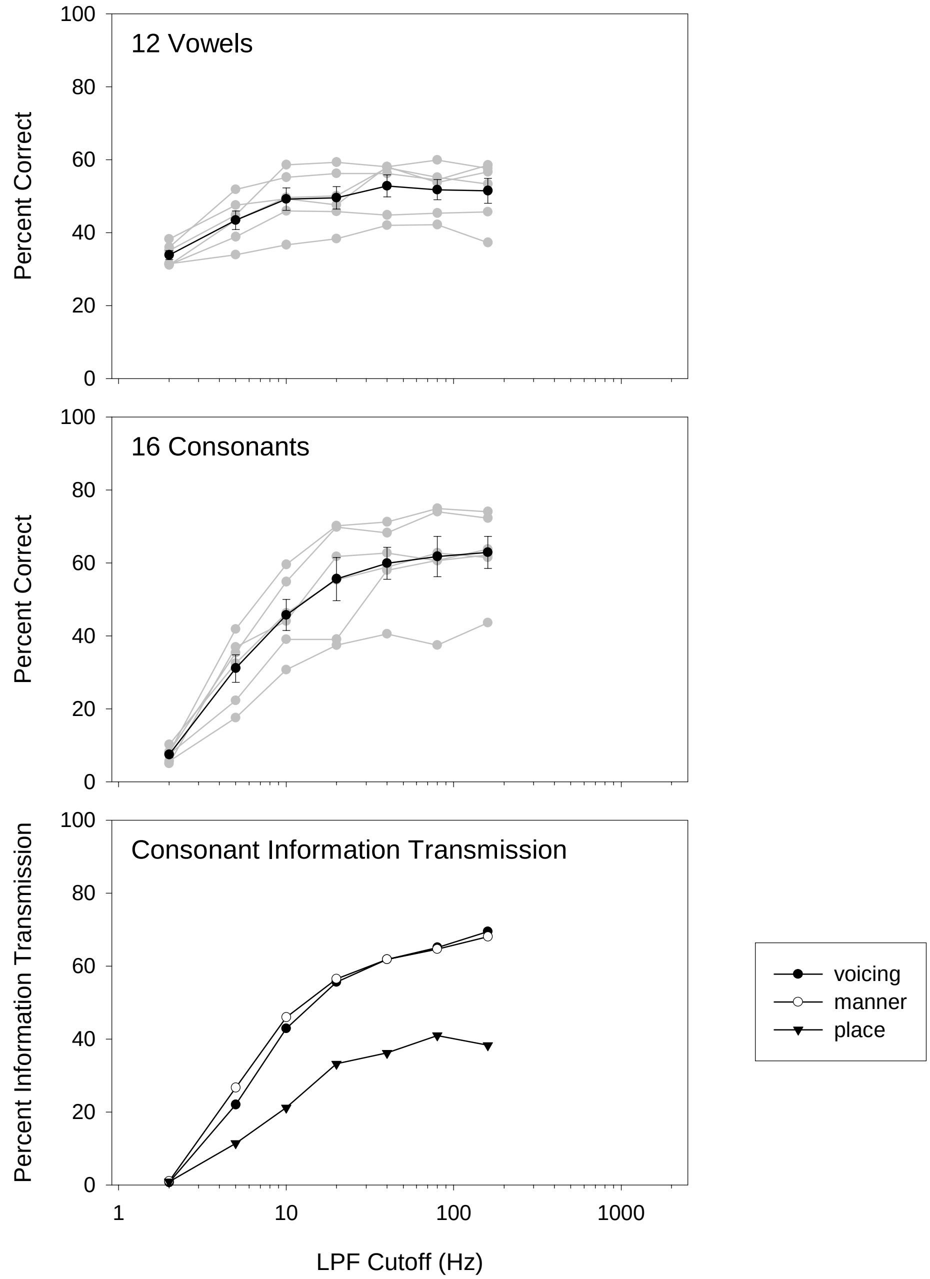

Fig. 23. Data from Fu and Shannon, 2000, showing effects of changes in lowpass cutoff frequencies. Results from tests with individual subjects are shown with the gray symbols and lines in the upper two panels, and means and standard errors of those scores are shown by the black symbols and lines. The bottom panel shows information transmission scores for the consonant features of voicing, manner and place. Note that the axis for lowpass cutoff is extended at the lower end relative to that axis for other figures in this report, to show scores for tested cutoffs below 10 Hz.

2 Hz to 20 Hz is much larger than the magnitude of the overall improvement from 20 Hz to 160 Hz (see middle panel of Fig. 23).

Information transmission scores for each of the consonant features increase monotonically with increases in lowpass cutoff from 2 Hz to 80 Hz. The scores for voicing and manner continue to

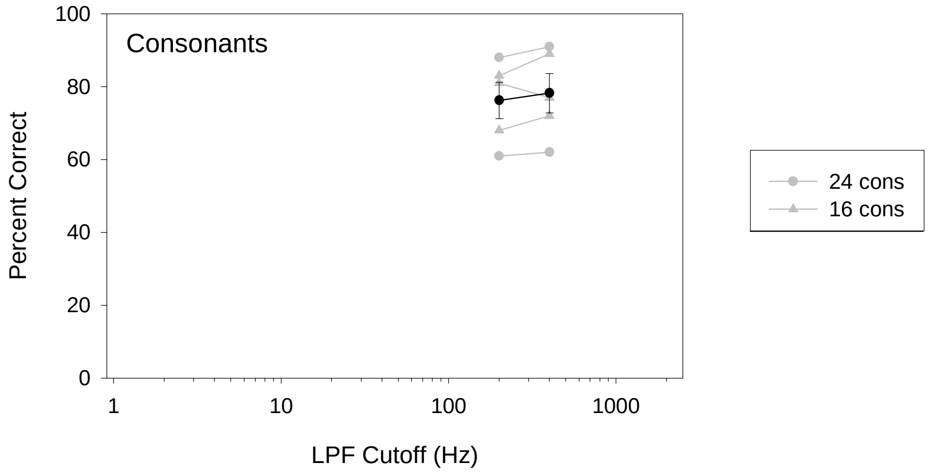

Fig. 24. Data from Lawson *et al.*, 1996, showing effects of changes in lowpass cutoff frequencies. Results from tests with individual subjects are shown with the gray symbols and lines, and means and standard errors of those scores are shown by the black symbols and lines. A 24-consonsont test was used with two of the subjects (gray circles), and a 16-consonant test was used with the remaining three subjects (gray triangles).

increase with the further increment in cutoff to 160 Hz, but the scores for place are about the same for the cutoffs of 80 and 160 Hz. The overall increase in scores, from 2 Hz to 160 Hz, is much greater for voicing and manner than for place.

As noted above, data from the study by Lawson *et al.*, 1996, are presented in Fig. 24. The lowpass cutoffs included in the tests of that study were 200 and 400 Hz, used in six-channel processors with a stimulus rate of 833 pulses/s/channel. Results from consonant tests with a male talker are shown in the figure; results from tests with a female talker were similar to those for the male talker.

A paired t test indicates that the difference in mean scores between the two lowpass cutoffs is not significant. This finding is consistent with findings from the present study and the study by Fu and Shannon. In particular, the collected findings indicate large improvements in speech reception scores with increases in lowpass cutoffs from low values up to cutoffs in a range between 20 and 100 Hz. In some cases further gains in speech reception can be obtained with further increases in cutoffs up to, but not beyond, 200 Hz.

Comparison of present results with those from other studies. Results from the present study bridge gaps and extend the ranges of other studies. Results from the present study also provide new information on effects of (1) conjoint changes in rate of stimulation and lowpass cutoff frequencies, (2) changes in rate in the absence of electrode interactions, and (3) changes in rate and lowpass cutoffs over exceptionally wide ranges for the same subjects.

In general, results from different studies show at least broad agreement in regions of overlap. Examples of such agreement are presented in Figs. 25 and 26, which show comparisons of results from the present study with results from the study by Fu and Shannon. Fig. 25 shows results for manipulations in lowpass cutoff frequency, and Fig. 26 shows results for manipulations in rate. Results from the study by Fu and Shannon are indicated with the gray symbols and lines, and results from the present study are indicated with the black symbols and lines.

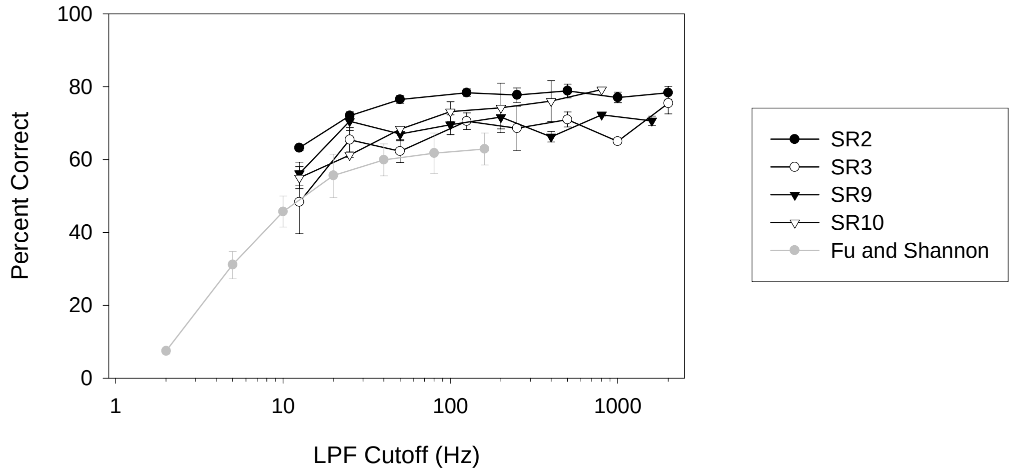

Fig. 25. Comparison of results obtained from tests of consonant identification in the present study (black symbols and lines, results reproduced from Fig. 10) with those of Fu and Shannon, 2000 (gray symbols and lines), for changes in lowpass cutoff frequencies.

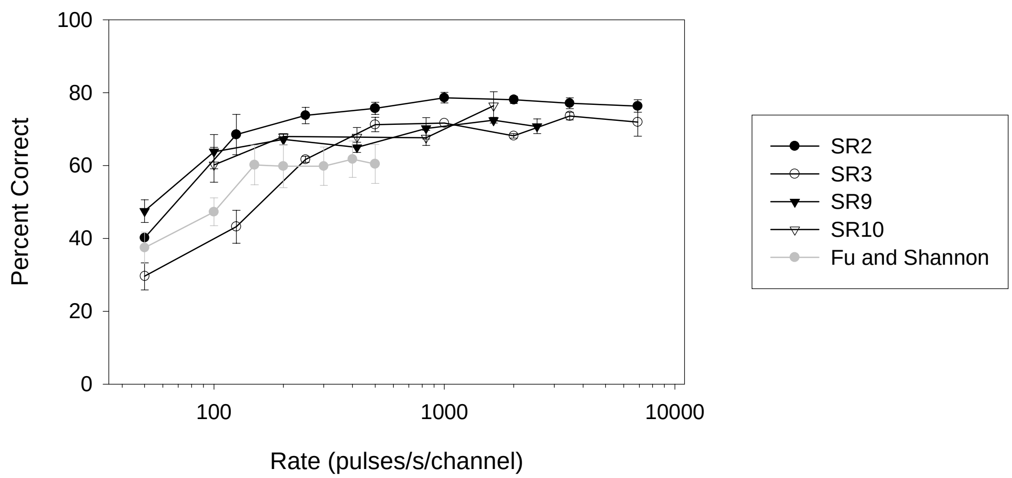

Fig. 26. Comparison of results obtained from tests of consonant identification in the present study (black symbols and lines, results reproduced from Fig. 11) with those of Fu and Shannon, 2000 (gray symbols and lines), for changes in rate of stimulation.

The results in Fig. 25 show agreement in the findings between the two studies in the region of overlap, from 12.5 Hz to 160 Hz. The results from the study by Fu and Shannon provide information about effects of manipulations in lowpass cutoff at frequencies below 12.5 Hz. The results from the present study provide information about effects (or lack thereof) of manipulations at frequencies above 160 Hz. The present results also provide information about differences in effects among subjects, and about the dependence of the effects on rate of stimulation, across a wide range of rates. As described before, improvements in consonant identification are observed with increases in cutoff from low values up to 25, 50 or 100 Hz, depending on the subject. Also, effects of manipulations in lowpass cutoff become more uniform for rates of stimulation at and above 200 pulses/s/channel. In some cases further increases in cutoff up to 200 Hz can produce further significant improvements in scores.

The results in Fig. 26 also show broad agreement in the region of overlapping rates between the two studies, *i.e.*, rates from 50 to 500 pulses/s/channel. The results from the present study also provide information about effects of manipulations in rate for rates above 500 pulses/s/channel. As described before, results from the study by Fu and Shannon indicate improvements in consonant identification with increases in rate from 50 to 150 pulses/s/channel. Results from the present study indicate improvements with increases in rate from 50 to 500 pulses/s/channel for subjects SR2 and SR3, from 50 to 100 pulses/s/channel for subject SR9, and from 100 to 1634 pulses/s/channel for subject SR10 (for lowpass cutoffs at and above 100 Hz). The present results also indicate a further significant increase in scores with an increase in rate up to 1634 pulses/s/channel for subject SR9.

Implications for speech processor design. Large increases in speech reception performance can be obtained with increases in rate of stimulation up to around 500 pulses/s/channel and with increases in lowpass cutoff to up to 50 to 200 Hz. Some patients will enjoy significant further gains in performance with further increases in rate; indeed, with rare exception the highest scores were achieved by each subject in the present study at the highest rate used for each test. Results from studies with one subject using a single-channel processor indicated that quite high rates (*e.g.*, 10000 pulses/s/channel) may be helpful, at least for situations in which electrode interactions can be eliminated or minimized.

Results from this and other studies indicate a high variability among subjects in effects of rate manipulations. Some subjects show monotonic increases in speech reception scores with increases in rate over wide ranges, whereas other subjects shows peaks or asymptotes in performance at intermediate rates (usually above 500 pulses/s/channel). We are not aware of any subject with a significant peak in performance below 500 pulses/s/channel.

A minimal specification for a processor design capable of supporting relatively high levels of performance for most patients would include at least four independent channels of stimulation, a stimulus rate of 500 pulses/s/channel, and a lowpass cutoff frequency of 100 Hz. Increases in the values for any one of these parameters may well produce improvements in performance for at least some patients. However, the largest gains in performance generally will be obtained by increasing the number of channels, rate and lowpass cutoff from lower values to the above values.

That being said, a higher number of channels, and a higher rate of stimulation, may be especially helpful for some patients. Increases in rate from the region 500 pulses/s/channel up to higher rates have produced improvements in speech reception for approximately half or more of the subjects in a variety of studies (present study; Brill *et al.*, 1998; Kiefer *et al.*, 2000; Loizou and Poroy, 1999). All six subjects studied by Loizou and Poroy (1999), for instance, obtained substantially higher scores for recognition of CNC monosyllabic words at the rate of 2100 pulses/s/channel than at 400 pulses/s/channel. As noted above, the means of the scores for these subjects were significantly higher at the rates of 800, 1400 and 2100 pulses/s/channel than at 400 pulses/s/channel.

In the great majority of cases, increases in rate from about 500 pulses/s/channel to approximately 2000 pulses/s/channel or higher either produce statistically equivalent scores or significant improvements in scores, depending on the subject and sometimes on the test. There is little to lose and much to gain (for at least some patients) by increasing rates over this range.

Results from other studies also have indicated that some patients may benefit from an increase in the number of channels from 4 to 6 or somewhat higher (see Background section). The number of perceptually independent electrodes and channels may be limited by interactions among the electrodes. As the electrodes are brought closer together, to increase the total number for a given longitudinal distance, interactions among the electrodes increase. At some point, any gain in increasing the number of channels and electrodes will be offset by the increasing level of interactions. Thus, with present electrode designs, more than 8 channels and electrodes probably would not produce gains in speech reception performance.

A reduction in interactions might change the above recommendations. Such a reduction may increase the number of useable (perceptually separable) channels and electrodes in an implant. It also may alter in a favorable way the likely tradeoff between improvements in the temporal representation versus increases in electrode interactions, with increases in rate of stimulation. With greatly reduced interactions, patients may be able to enjoy the benefits suggested by the results obtained in the present study with single-channel processors. In particular, in the absence of interactions, subject SR2 achieved significantly higher scores in tests of sentence recognition using the rate of 10162 pulses/s versus the rates of 2525 or 833 pulses/s.

Future studies. Future studies should include field trials with high-rate processors. Subjects in the present study commented that bench processors using rates of stimulation at and above about 5000 pulses/s/channel sounded especially natural and intelligible. In some cases, scores from objective tests demonstrated an immediate improvement with such processors compared with other (lower rate) processors, and in other cases the scores did not indicate a significant difference between the two types of processor. In any case, performance with a new processing strategy can improve with experience (typically over a period ranging from several weeks to several months; see, *e.g.*, Lawson *et al.*, 1999, and Pelizzone *et al.*, 1999) and field trials would allow evaluation of the full potential of high-rate processors.

Work to date has not included evaluation of changes in rate and lowpass cutoff for speech reception in noise. Results may well be different for speech in noise, and tests with consonants or other speech material at various speech-to-noise ratios should be conducted.

In addition, the results of Loizou and Poroy indicate the likely importance of vowel context for identification of consonants. Some of the basic tests of the present study should be repeated with different vowel contexts. Further, measures with different talkers for consonant test would allow evaluation of possible talker (*e.g.*, gender of talker) effects.

Future studies also should include a repetition of the key tests in the present study when subjects with new "modiolar hugging" electrodes become available. Those electrodes, under development by each of the major manufacturers of cochlear implants and cooperating universities (see Wilson, 2000a, for a brief description of these efforts), may well produce large reductions in electrode interactions. As described above, such reductions may alter in a favorable way a possible tradeoff between improvements in the representation of envelope signals versus increases in electrode interactions, with increases in rate. If electrode interactions can be largely eliminated, or at least minimized, then relatively high rates may prove to be helpful for most or all patients.

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III. Plans for the next quarter

Our plans for the next quarter include the following:

- Studies with Ineraid subject SR3 during the two weeks beginning on April 3. We expect that the studies will include (1) longitudinal measures with her portable CIS (CIS-Link) processor, (2) measures of consonant identification and sentence recognition for CIS processors using a wide range of compression functions, and (3) evaluation of "conditioner pulses" processors.
- Studies with the first of several subjects implanted with short electrodes (insertion depths of 20 mm or less) and with preserved low-frequency hearing, referred to us by our colleagues at the J.W. Goethe Universität in Frankfurt, Germany. The studies will include evaluation of various strategies for combined electric and acoustic stimulation of the same cochlea.
- Studies with recipients of bilateral CI24M implants, referred to us by our colleagues at the University of Iowa. Such studies ultimately will include up to ten subjects, and we expect to work with the first one or two of those subjects in the next quarter. Studies with each of the subjects will include measures of sensitivities to interaural timing and amplitude differences and evaluation of various processing strategies designed to represent with high fidelity cues for sound localization or to exploit the availability bilateral implants in other ways (see Quarterly Progress Report 4 for this project, for a detailed discussion of processing options for bilateral implants).
- Presentation of project results in an invited talk by Wilson at the conference on *Binaural Hearing, Hearing Loss, and Hearing Aids*, to be held at the University of Iowa, June 22-24.
- Completion of the Access database of processor designs and study results (see Introduction).
- Continued development of a new strategy, designed to mimic closely the nonlinear processing in the normal peripheral auditory system, including the strong and nearly instantaneous compression at the basilar membrane for sound pressure levels above 35-40 dB and the strong and noninstantaneous (with multiple time constants) compression that occurs at the synapse between inner hair cells and type I fibers of the auditory nerve.
- Continued analysis of psychophysical, speech reception, and evoked potential data from current and prior studies.
- Continued preparation of manuscripts for publication.

We note that the above plans do not include studies with Ineraid subject SR2 for the first time in a long time. He is moving from the Research Triangle area to Wisconsin in early April. We will miss seeing him each week, but expect that he will resume the periodic visits he made to our laboratory prior to his move to North Carolina several years ago. Such return visits are greatly anticipated by him and by us.

We also note that SR2 probably has contributed more time and insights than any other subject in the history of cochlear implant research. He has worked for many years with our group and the group at the Massachusetts Eye & Ear Infirmary in Boston. He also has worked with other groups in the United States and Europe for shorter periods. He has been the pioneer subject for many important developments in our field. His contributions have had an enormous positive impact on progress in cochlear implants and on the lives of implant users. We admire him as a person and are most grateful for everything he has done on behalf of our research and his fellow implant patients.

IV. Announcements

Charles Finley accepted a position with the University of North Carolina during this quarter. His new position will be funded by the Advanced Bionics Corporation for the year beginning February 1, 2000, his approximate start date at UNC.

Dr. Finley has made many important contributions to our efforts over the years and will be missed. He will not be lost to the field of cochlear prostheses, however, and he also has agreed to serve as a consultant to our project at RTI, to assure continued development over the short term of systems for measurement of intracochlear evoked potentials and to assure a smooth transition for continuation of EP studies at RTI by Blake Wilson, Lianne Cartee, and Robert Wolford. (Dr. Cartee will resume her active involvement in the project beginning in May, 2000.)

Reinhold Schatzer became a member of the RTI team on March 1, 2000. He earned his Master's degree in Physics at the University of Innsbruck in 1997 with high honors and also worked at the Med El company in Innsbruck for nearly two years after that. One of his principal responsibilities at Med El was assembly-language programming of the DSP 56000 series of chips to implement advanced signal-processing strategies for cochlear implants. He also was involved with hardware design and testing. He is fluent in the C, C++, Fortran, Pascal, Java, Basic, MATLAB, and LABVIEW programming languages. He has expertise in the design and application of XILINX FPGA digital circuits. We expect that he will apply these and other skills in assuming the responsibilities previously held by Marian Zerbi of the RTI team. Those responsibilities include implementation of real-time speech processor designs, development of software for support of psychophysical and evoked potential studies, and design and fabrication of custom electronic equipment as required by our various studies. We are very pleased to have Mr. Schatzer as a member of our team.

A final announcement for this quarter is that Blake Wilson has accepted an invitation to serve on the editorial board for a new journal, *Cochlear Implants International*. The journal will be published by the Whurr Publishing Company in London and will be the first journal devoted to the field of cochlear prostheses.

V. Acknowledgments

We thank subjects SR2 and SR15 for their participation in the studies of this quarter. We also would like to thank again subjects SR2, SR3, SR9 and SR10, for their participation in studies of prior quarters, as described in section II of this report. We are grateful to Marian Zerbi, Charles Finley and Chris van den Honert for their technical contributions in support of various parts of the studies described in section II.

We also would like to thank Joachim Müller of the Julius-Maximilians Universität in Würzburg, Peter Nopp of the Med El company in Innsbruck, Arturs Lorens of the Institute of Physiology and Pathology of Hearing in Warsaw, and Lianne Cartee of our group at RTI for their excellent presentations at the "Mini Symposium on Cochlear Implants," held at RTI on February 7, 2000.

Appendix 1. Summary of reporting activity for this quarter

Reporting activity for this quarter, covering the period of January 1 through March 31, 2000, included the following:

Presentations

Wilson BS: New directions in cochlear implants. Invited lecture presented at the *6th International Cochlear Implant Conference*, Miami Beach, FL February 3-5, 2000.

van den Honert C, Finley CC, Wilson BS: Measurement of intracochlear evoked potentials. Presented at the *6th International Cochlear Implant Conference*, Miami Beach, FL February 3-5, 2000.

Brill S, Kerber M: Electrode discrimination along the cochlea based on pitch perception. Presented at the *6th International Cochlear Implant Conference*, Miami Beach, FL February 3-5, 2000. (This presentation reported results previously collected by the authors in Innsbruck; preparation of the talk, and participation in the conference, was supported by the present project.)

Tyler RS, Parkinson A, Wilson BS, Witt S, Gantz B, Rubinstein J, Wolaver A, Lowder M: Binaural cochlear implants and hearing aids and cochlear implant: Speech perception and localization. Presented at the *6th International Cochlear Implant Conference*, Miami Beach, FL February 3-5, 2000. (Wilson's participation in this effort was jointly supported by the Program Project Grant on Cochlear Implants at the University of Iowa and by the present project.)

Wilson BS: Chair, *Mini Symposium on Cochlear Implants*, Research Triangle Park, NC, February 7, 2000.

Appendix 2. Mini Symposium on Cochlear Implants

A Mini Symposium on Cochlear Implants was held at RTI on February 7, 2000, following the *6th International Cochlear Implant Conference* held in Miami Beach, FL, the week before. The Mini Symposium allowed much longer talks and greater discussion on selected topics, compared with the conference in Miami. The agenda for the Mini Symposium is reproduced below.

Mini Symposium on Cochlear Implants

Monday, February 7, 2000, 1pm
Herbert 258

Comparison of Scala Tympani and Intrameatal Electrical Stimulation Responses of Cochlear Neurons, Lianne Cartee, Ph.D., Research Scientist, Research Triangle Institute, Research Triangle Park, NC

Bilateral Cochlear Implantation, Joachim Müller, MD PhD., Director of Cochlear Implant Program and Otologic Surgeon, University of Würzburg, Germany

Overview of Research in Innsbruck, Peter Nopp, Ph.D., Director of Research, MedEl GmbH, Innsbruck, Austria

Psychophysical Measurements for Cochlear Implant Fitting, Artur Lorens, MSEE, Scientist, Institute of Physiology & Pathology of Hearing, Warsaw, Poland

Appendix 3: Supplemental data for Section II

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

Lowpass Cutoff (Hz)

Fig. A.1. Percent correct scores and standard errors of the means for identification of consonants in quiet, male talker, subject SR2.

Rate (pulses/s/channel)	12.5	25	50	125	250	500	1000	2000
50	40.4 ±3.2	25.8 ±1.8	33.3 ±3.8					
125	32.1 ±3.3	50.0 ±2.2	45.0 ±3.7	34.6 ±2.5				
250	39.6 ±1.8	62.1 ±2.1	59.2 ±2.7	62.9 ±2.5	62.5 ±3.8			
500	57.1 ±4.0	68.8 ±1.9	65.4 ±2.0	76.7 ±1.9	74.6 ±2.4	70.8 ±2.2		
1000				71.7 ±2.2				
2000				68.8 ±1.7		67.5 ±2.3		
3500						74.6 ±1.6		72.5 ±2.5
6900				72.5 ±2.0			65.0 ±1.9	78.3 ±3.8

Lowpass Cutoff (Hz)

Fig. A.2. Percent correct scores and standard errors of the means for identification of consonants in quiet, male talker, subject SR3. Conditions for the empty cells were not tested. Only the data for the completed part of the matrix (top half) are shown in the contour plots of Figs. 1-3.

Rate (pulses/s/channel)	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

Lowpass Cutoff (Hz)

Fig. A.3. Percent correct scores and standard errors of the means for identification of consonants in quiet, male talker, subject SR9.

Rate (pulses/s/channel) \ Lowpass Cutoff (Hz)	12.5	25	50	100	200	400	800
100	63.8 ±2.2	65.0 ±2.2	55.4 ±3.0				
200			67.1 ±3.9	68.8 ±4.0			
417	56.7 ±2.4	60.0 ±2.9	69.6 ±2.4	70.4 ±1.9	71.3 ±2.9		
833	49.2 ±1.9	61.3 ±2.3	69.6 ±2.2	72.5 ±2.4	64.2 ±2.7	70.4 ±3.8	
1634	59.2 ±2.2	62.5 ±2.9	67.1 ±3.1	80.8 ±2.9	87.1 ±2.7	81.7 ±1.8	79.2 ±2.5

Fig. A.4. Percent correct scores and standard errors of the means for identification of consonants in quiet, male talker, subject SR10.