Eighth Quarterly Progress Report

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Speech Processors for Auditory Prostheses

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CONTENTS

I. Introduction

One of the principal objectives of this project is to design, develop, and evaluate speech processors for implantable auditory prostheses. Ideally, the processors will represent the information content of speech in a way that can be perceived by implant patients. Another principal objective is to develop new test materials for the evaluation of speech processors, given the growing number of cochlear implant subjects enjoying levels of performance too high to be sensitively measured by existing tests.

Work in the present quarter included:

- Continued studies with Ineraid subject SR10, for the period of April 21 to May 2, 1997. Studies during this visit included (a) measures of intracochlear evoked potentials (EPs) for unmodulated and sinusoidally amplitude modulated pulse trains with pulse rates up to 10000/s; (b) measures of intracochlear EPs for pairs of identical pulses with several amplitudes and a wide range of interpulse intervals; (c) measures to verify operation of and identify remaining problems with new stimulating and recording systems for EP studies; (d) measures of electrically evoked auditory brainstem responses (EABRs) for all six electrodes; (e) measures of consonant identification for CIS processors with different numbers of channels and various channel to electrode assignments; and (f) measures of consonant identification for six-channel CIS processors using various rates of stimulation up to 10000 pulses/s/channel.
- Studies with Ineraid subjects SR15 (June 2-6), SR16 (June 16-20), and SR9 (July 28 to August 1), principally to begin evaluation of possible learning effects with chronic use of a portable CIS processor. Each subject was fit with the Innsbruck/RTI (“CIS-Link”) processor, and each subject will return to the laboratory for longitudinal measures of speech reception performance following six months of daily experience with that processor. Subject SR16 also was given recorded tests of consonant identification for use at home, to be taken at two-week intervals during the first two months, as previously described for subject SR3 (Quarterly Progress Report 1, pages 5-13). Additional studies with subjects SR15, SR16 and SR9 included psychophysical scaling experiments like those described in our Quarterly Progress Report 7 for subject SR2, along with measures of intracochlear EPs for a variety of stimuli. Stimuli for the EP measures for subjects SR16 and SR9 included those used in the psychophysical experiments.
- Studies with Ineraid subject SR3 (July 7-18), including (a) a repeated set of tests to evaluate possible continuing learning effects with the potable Innsbruck/RTI processor first applied for this subject in April, 1995; (b) evaluation of various “high rate” processors, using pulse rates up to 10000 pulses/s/channel; (c) psychophysical experiments like those described in Quarterly Progress Report 7 for subject SR2; (d) measures of intracochlear evoked potentials for a variety of stimuli including the stimuli used in the psychophysical experiments; (e) recordings of EABRs to 50 pulses/s stimuli for all six electrodes; (f) cross-calibration of new speech test materials developed in this project; and (g) measures of consonant identification for CIS processors with different numbers of channels and various channel to electrode assignments.
- Ongoing studies with Ineraid subject SR2 (usually one morning per week). Studies in this quarter included measures of intracochlear EPs for a variety of stimuli with high pulse rates and measures of consonant identification for CIS processors with different numbers of channels and various channel to electrode assignments.

- Continued preparation for studies with bilateral patients, and continued development of the speech reception and evoked potential laboratories
- Presentation of project results in invited lectures at the Vth International Cochlear Implant Conference in New York City (May 1-2), the 131st annual meeting of the American Otological Society in Scottsdale, AZ (May 10-11), and for the Department of Biomedical Engineering at Johns Hopkins University (May 30).
- Continued analysis of speech reception and evoked potential data from prior studies.
- Continued preparation of manuscripts for publication.

A highlight of the last quarter was recognition by the American Otological Society of work in this project. Project team members Wilson, Lawson, Finley and Zerbi received the President's Citation, for "Major contributions to the restoration of hearing in profoundly deaf persons," on the occasion of the 131st annual meeting of the American Otological Society, held in Scottsdale, AZ, May 10-11, 1997. We are especially proud of this great honor.

In this report we present comparisons of temporal patterns of auditory nerve activity with judgments of pitch for cochlear implant subjects. The stimuli included unmodulated and sinusoidally amplitude modulated (SAM) pulse trains. Pulse rates for the unmodulated pulse trains ranged from 100 to 600/s, and modulation frequencies for the SAM pulse trains ranged from 100 to 600 Hz. The patterns of nerve response for these stimuli were measured with recordings of intracochlear evoked potentials, and pitch judgments for the same stimuli were measured with a magnitude estimation procedure.

In broad terms, the comparisons show high correlations for some but not all subjects between the psychophysical and electrophysiological measures. In cases of low or insignificant correlations judgments of pitch do not increase with decreases in the principal interval(s) of the nerve response. This suggests that the central nervous system in such cases is not able to utilize representations of intervals at the periphery, which appear to be robust for all studied conditions and subjects. A lack of correlation between peripheral representations and perception may explain at least in part why some subjects do not enjoy high levels of performance with present implant systems and processing strategies. Subjects in our series who exhibited low or insignificant correlations also had the lowest speech reception scores. Knowledge of the "disconnect" between temporal patterns of neural activity and perception for such subjects may lead to the development of new processing strategies, e.g., strategies that emphasize representations of spatial or tonotopic cues through tradeoffs that can be achieved with reductions in the range over which temporal cues are represented.

II. Relationships Between Temporal Patterns of Nerve Activity and Pitch Judgments for Cochlear Implant Patients

In our last progress report for this project we described patterns of auditory nerve responses for unmodulated pulse trains over a wide range of pulse rates and for sinusoidally amplitude modulated (SAM) pulse trains over wide ranges of modulation frequencies and carrier rates. In addition, we presented results of a psychophysical scaling experiment, in which subject SR2 provided judgments of pitch for unmodulated and SAM pulse trains that differed somewhat (e.g., in amplitude) from the stimuli used in the electrophysiological measures. In this report we describe direct comparisons of psychophysical and electrophysiological measures using the same stimuli for four subjects. In addition, we describe scaling results for two other subjects for reference. The electrophysiological measures still need to be made for these subjects, scheduled for their next visits to the laboratory.

Subjects and stimuli

All six subjects who participated in these studies are experienced users of the Ineraid implant. They also represent a broad range of clinical performance with that and other implant systems. Subject SR2 is among the several top patients in the world in terms of his speech reception performance with the implant and a CIS processor, whereas subject SR15 is among the world's worst patients with her clinical CA processor and only somewhat better with an acute fitting of a CIS processor. SR15 does not enjoy any measurable open set recognition of speech with the CA processor, and scores for the CIS processor are above zero but still quite low. (This subject is participating in a field trial using a portable processor that implements a CIS algorithm. Insofar as results with other subjects are a guide, her scores with the CIS processor may improve with experience.) Subject SR3 enjoys excellent speech reception performance with her implant in conjunction with a CIS processor. Subjects SR10 and SR16 are in a middle category of performance, between excellent and poor, with their implants and a CIS processor. Their performances with the clinical CA processor are poor.

The stimuli included 200 ms bursts of unmodulated or SAM pulse trains, presented at a most comfortable loudness level (MCL) for all conditions. Six conditions were studied for each of five carrier rates for the SAM pulse trains, and six conditions were studied for the unmodulated pulse trains. The carrier rates included 504, 1016, 2032, 5081 and 10162 pulses/s. The conditions for the SAM pulse trains included 100 percent modulation at frequencies of 100 through 600 Hz at 100 Hz intervals. The conditions for the unmodulated pulse trains included the corresponding pulse rates of 100 through 600 pulses/s. Balanced biphasic pulses were used throughout, with a pulse duration of 33 µs/phase. All stimuli were delivered to intracochlear electrode 3 for all subjects. (This electrode is in the middle of the array of six electrodes in the Ineraid implant.)

Separate psychophysical scaling experiments were conducted for each of the carrier rates and for the unmodulated pulse trains for all subjects except SR15, whose tests did not include unmodulated pulse trains and one of the carrier rates (10162 pulse/s). The amplitudes of the stimuli were adjusted prior to each psychophysical experiment as necessary to eliminate any differences in loudness across conditions. A sweep across conditions was played for the subject following adjustment(s) in the amplitude(s) of one or more of the stimuli. Adjustments and sweeps were repeated until all six conditions for a particular experiment were judged to be equally loud and at MCL. The stimulus amplitudes determined in this way for each of the subjects and conditions are presented in Table 1.

Table 1. Stimulus levels.

Stimulus type	Mod freq (Hz) or pulse rate (pps)	Carrier level or pulse amplitude (μA)					
		SR2	SR3	SR9	SR10	SR15	SR16
504 pps carrier	100	714.2	977.3	492.5	695.5	912.7	530.5
	200	765.5	991.7	469.0	696.7	940.9	530.5
	300	823.4	991.7	469.0	696.7	912.7	546.4
	400	739.3	991.7	492.5	696.7	934.7	546.4
	500	712.9	934.8	492.5	717.6	788.0	562.8
	600	784.0	962.8	492.5	696.7	885.7	546.4
1016 pps carrier	100	672.2	929.4	448.9	656.7	912.7	562.8
	200	695.9	872.3	443.2	656.7	776.9	579.6
	300	761.0	856.9	424.4	656.7	799.5	596.5
	400	704.4	856.9	425.4	632.6	800.9	626.0
	500	724.3	882.6	446.7	676.4	776.9	644.8
	600	711.2	831.9	425.4	637.6	776.9	607.8
2032 pps carrier	100	702.3	808.1	359.2	587.0	810.9	517.1
	200	713.0	848.5	359.2	570.0	764.0	562.8
	300	721.5	841.0	351.8	570.0	678.8	562.8
	400	729.7	840.3	351.8	587.0	720.2	613.9
	500	689.5	806.1	351.8	587.0	720.2	579.2
	600	711.2	841.0	369.4	587.0	763.0	579.2
5081 pps carrier	100	628.9	631.7	256.5	497.4	665.8	354.9
	200	591.2	666.9	253.3	510.5	629.9	377.0
	300	564.4	686.9	265.9	491.9	594.2	388.3
	400	592.7	660.0	281.4	506.7	622.1	411.9
	500	588.7	660.0	281.4	506.7	603.4	424.3
	600	527.0	660.0	281.4	537.6	603.4	437.1
10162 pps carrier	100	493.6	468.1	236.7	397.3		341.2
	200	456.0	521.4	239.6	402.0		368.9
	300	479.7	525.3	239.6	422.1		371.0
	400	474.6	536.3	229.7	422.1		382.7
	500	470.1	501.0	229.7	428.7		394.0
	600	450.2	516.1	229.7	446.7		405.2
unmodulated pulses	100	812.5	989.9	556.0	716.4		590.9
	200	774.7	952.6	402.0	619.0		589.9
	300	708.9	889.9	359.1	619.0		559.2
	400	647.4	807.2	349.3	601.0		616.6
	500	593.2	738.7	359.2	583.5		564.8
	600	559.1	738.7	369.4	583.5		587.4

Plots of normalized pulse amplitudes for the SAM pulse train conditions are presented in Figs. 1-6. Figs. 1-3 show the first 100 ms of all stimuli, whereas Figs. 4-6 show the first 20 ms. Fig. 7 shows the entire 200 ms of the stimuli for the 504 and 1016 pulse/s conditions, to illustrate certain sampling artifacts for modulation frequencies approaching or exceeding either the Nyquist frequency (one-half the carrier rate) or the carrier frequency. Plots for the unmodulated pulse train conditions would of course show uniform amplitudes at 1.0.

Patterns of stimulation for modulation frequencies that are low compared to the carrier rate are sinusoidal or nearly so. This may be seen for 100 Hz modulation for all carrier rates and for higher modulation frequencies as carrier rate is increased. Patterns of stimulation are sinusoidal for all modulation frequencies for the 5081 and 10162 pulses/s carriers (Figs. 5 and 6).

As the modulation frequency approaches the Nyquist frequency, the sampling of the modulation waveform becomes sparse and the pattern of stimulation departs from a simple sinusoid. This may be seen, for example, in the panels for 200 Hz modulation of the 504 pulses/s carrier (Figs. 1 and 4).

Increases in modulation frequency beyond the Nyquist frequency produce a “mirroring” effect, in which the pattern of stimulation for a modulation frequency above the Nyquist frequency is identical to the pattern for a modulation frequency below the Nyquist frequency by an equal amount. Such a situation is approximated in the 200 and 300 Hz modulation conditions for the 504 pulses/s carrier. The difference between the modulation frequency of 300 Hz and the Nyquist frequency of 252 Hz is almost the same as the difference between the modulation frequency of 200 Hz and the Nyquist frequency. Consequently, there is a strong similarity in the patterns of stimulation for these two modulation frequencies (Figs. 1 and 4).

Strong similarities also are observed for 400 and 600 Hz modulation of the 1016 pulses/s carrier (Figs. 1 and 4). Again, the difference between the modulation frequency of 600 Hz and the Nyquist frequency of 508 Hz is similar to the difference between the modulation frequency of 400 Hz and the Nyquist frequency.

A mirroring effect also is produced with modulation frequencies that are equal distances away from the carrier frequency. This may be seen in the almost identical patterns of stimulation for 400 and 600 Hz modulation of the 504 pulses/s carrier. Note also that the intervals between principal peaks in the patterns of stimulation closely approximate the intervals for the 200 and 300 Hz modulation conditions. The 100 Hz separation between the 400 or 600 Hz modulation frequencies and the 504 pulse/s carrier rate corresponds to the 50 Hz separation between the 200 or 300 Hz modulation frequencies and the 252 Hz Nyquist frequency.

A close approximation of the modulation frequency to either the Nyquist frequency or the carrier frequency can produce severe sampling artifacts. Such artifacts are observed for 500 Hz modulation of the 504 pulses/s carrier, and for 500 Hz modulation of the 1016 pulses/s carrier (Figs. 1, 4 and 7). Both conditions show “beating” effects of interactions between the modulation frequency and the Nyquist or carrier frequencies. The difference between the 500 Hz modulation frequency and the carrier rate of 504 pulses/s carrier produces a beat frequency of 4 Hz, with a period of 250 ms. Most of the first cycle of that period is shown in the 200 ms record for 500 Hz modulation of the 504 pulses/s carrier in Fig. 7. Similarly, the close approximation of 500 Hz modulation and the Nyquist frequency of 508 Hz produces a strong beating effect for the combination of that modulation frequency and the 1016 pulse/s carrier (Figs. 1 and 7). For this condition, the beat frequency is 16

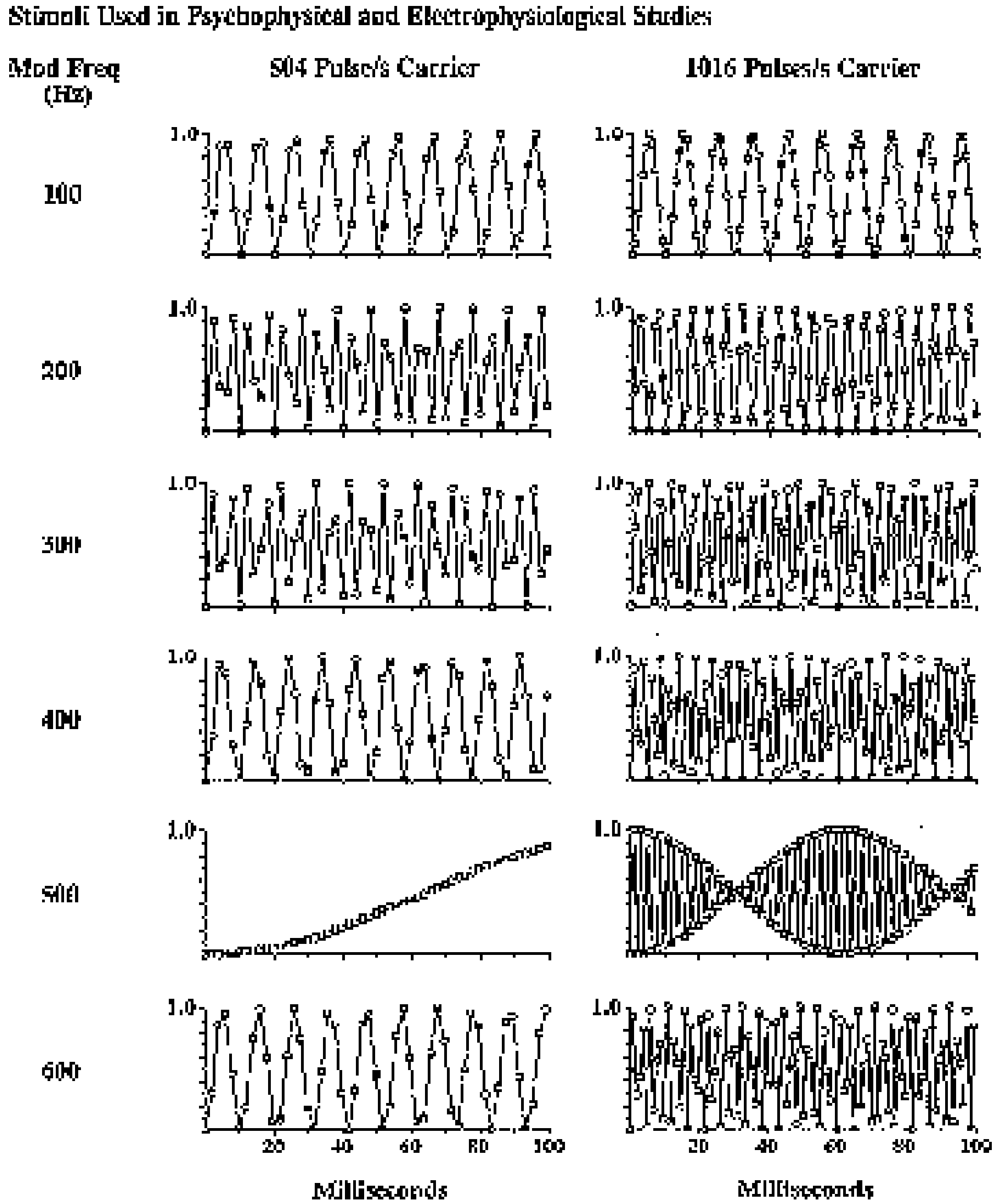


Fig. 1. Normalized amplitudes of stimulus pulses for the SAM pulse trains using the 504 and 1016 pulses/s carriers. The initial 100 ms of the 200 ms records is shown. Modulation frequencies are indicated in the left column.

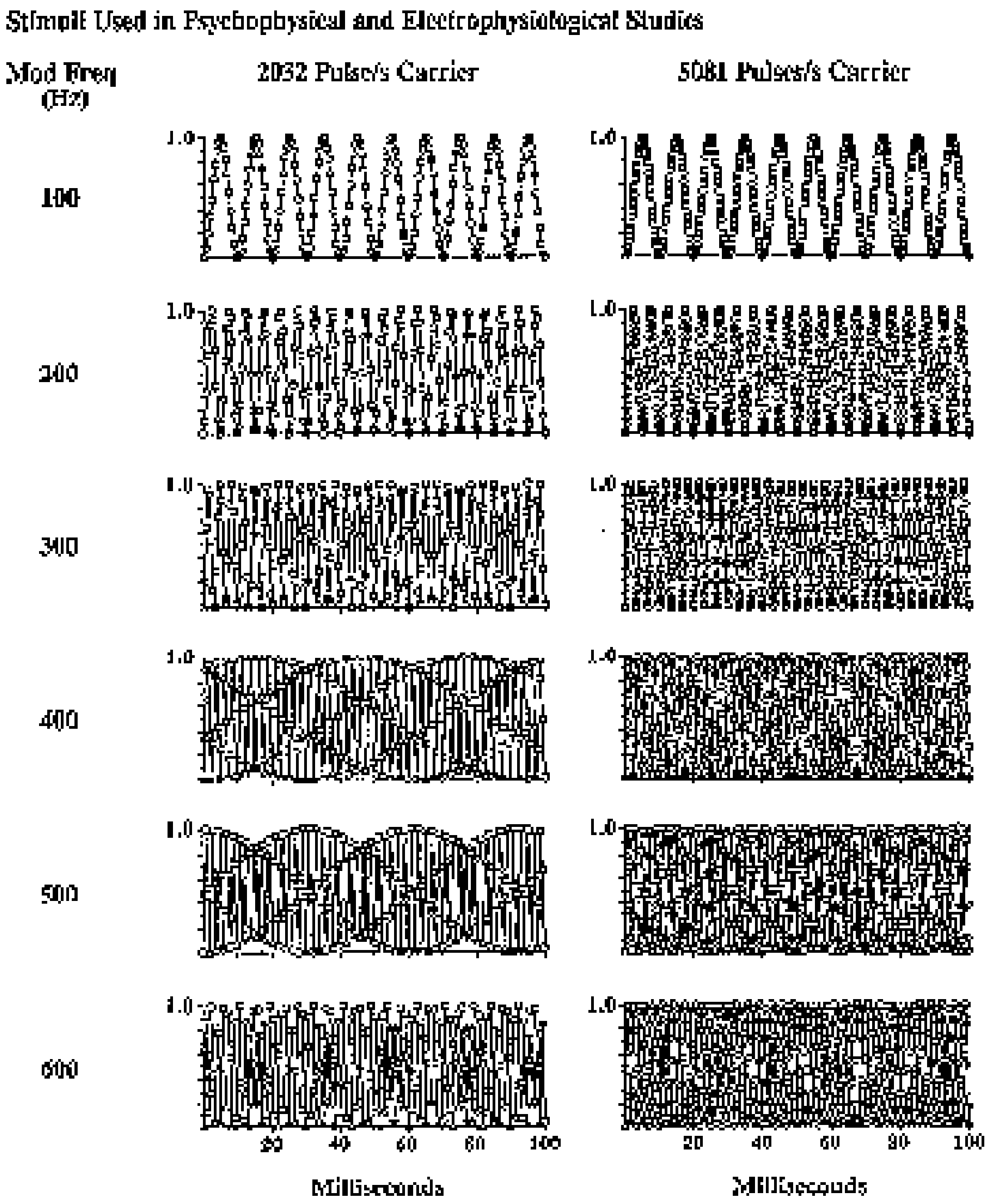


Fig. 2. Normalized amplitudes of stimulus pulses for the SAM pulse trains using the 2032 and 5081 pulses/s carriers. The initial 100 ms of the 200 ms records is shown. Modulation frequencies are indicated in the left column.

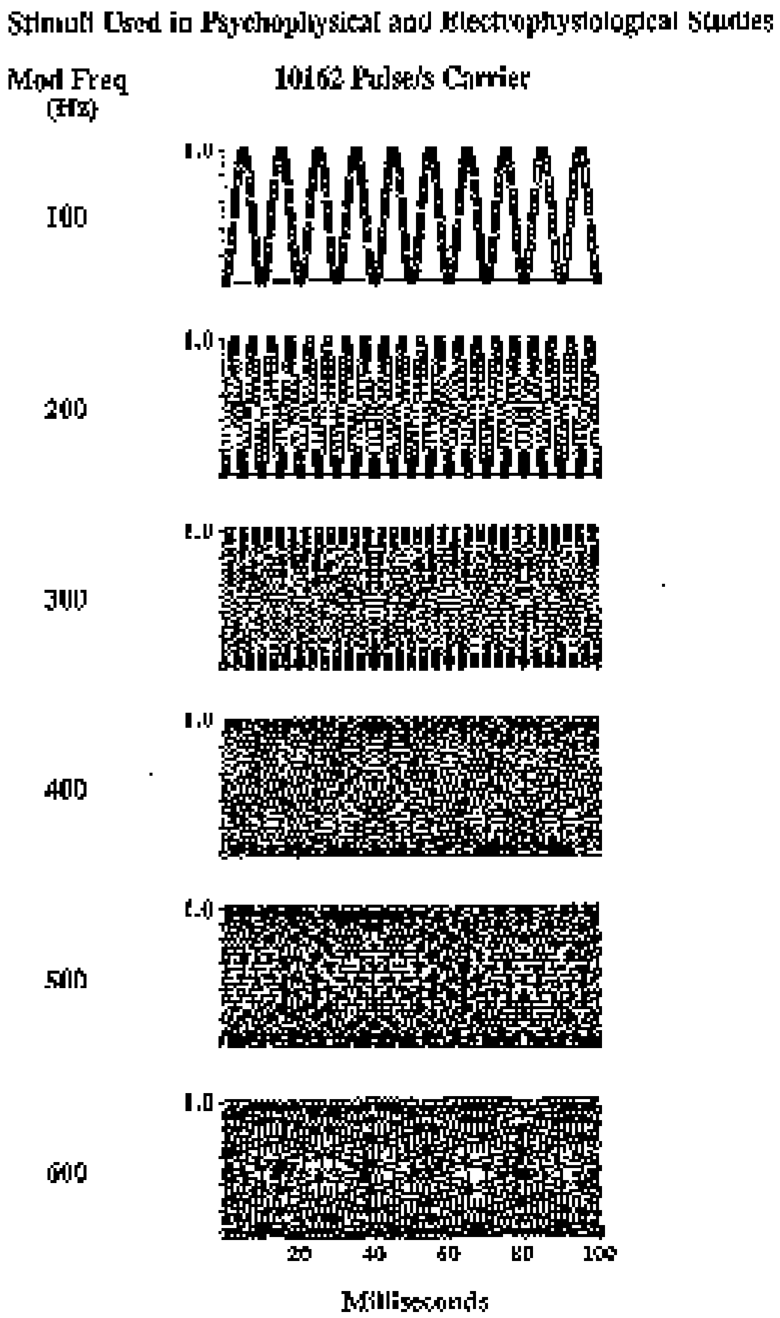


Fig. 3. Normalized amplitudes of stimulus pulses for the SAM pulse trains using the 10162 pulses/s carrier. The initial 100 ms of the 200 ms records is shown. Modulation frequencies are indicated in the left column.

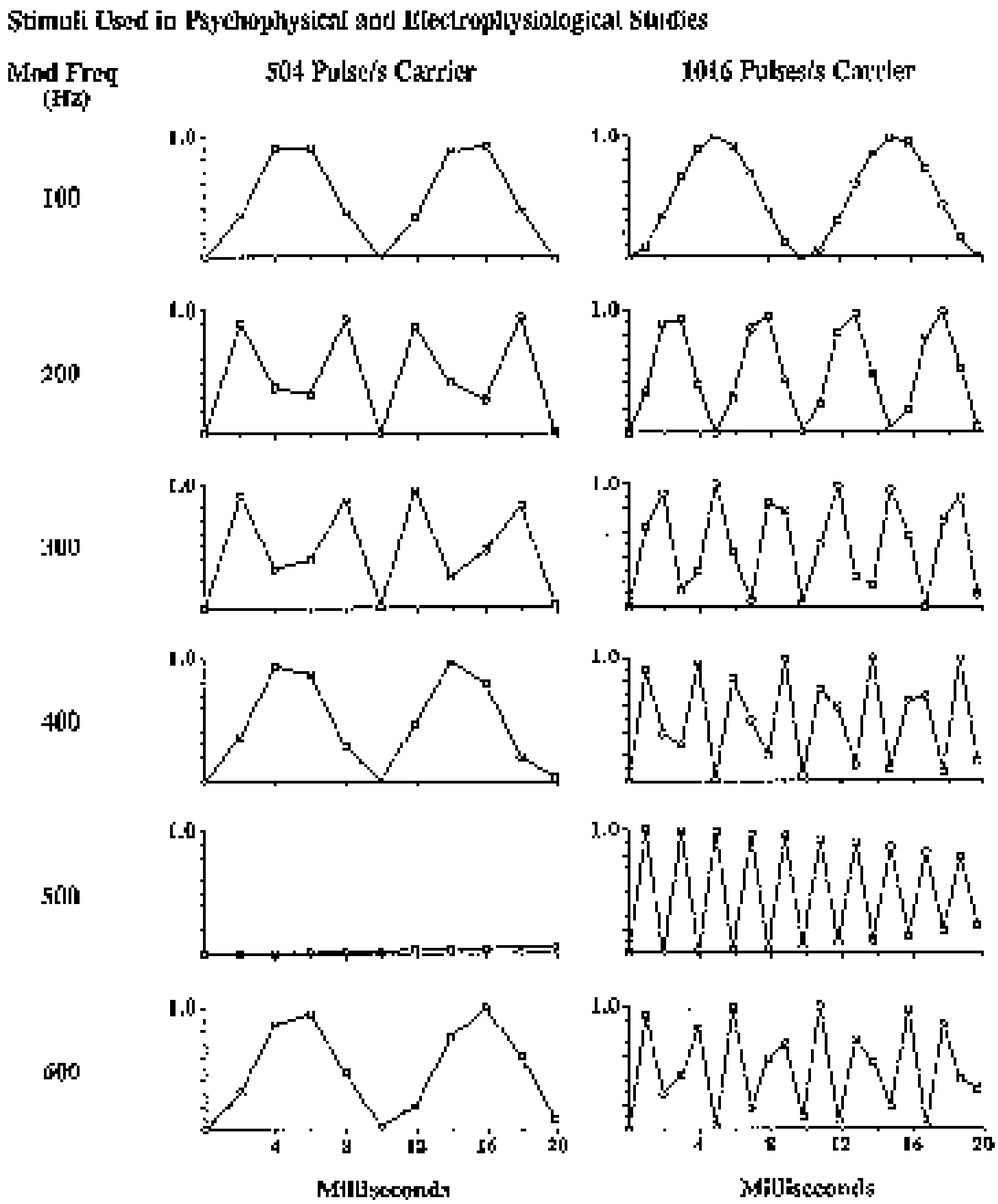


Fig. 4. Normalized amplitudes of stimulus pulses for the SAM pulse trains using the 504 and 1016 pulses/s carriers. The initial 20 ms of the 200 ms records is shown. Modulation frequencies are indicated in the left column.

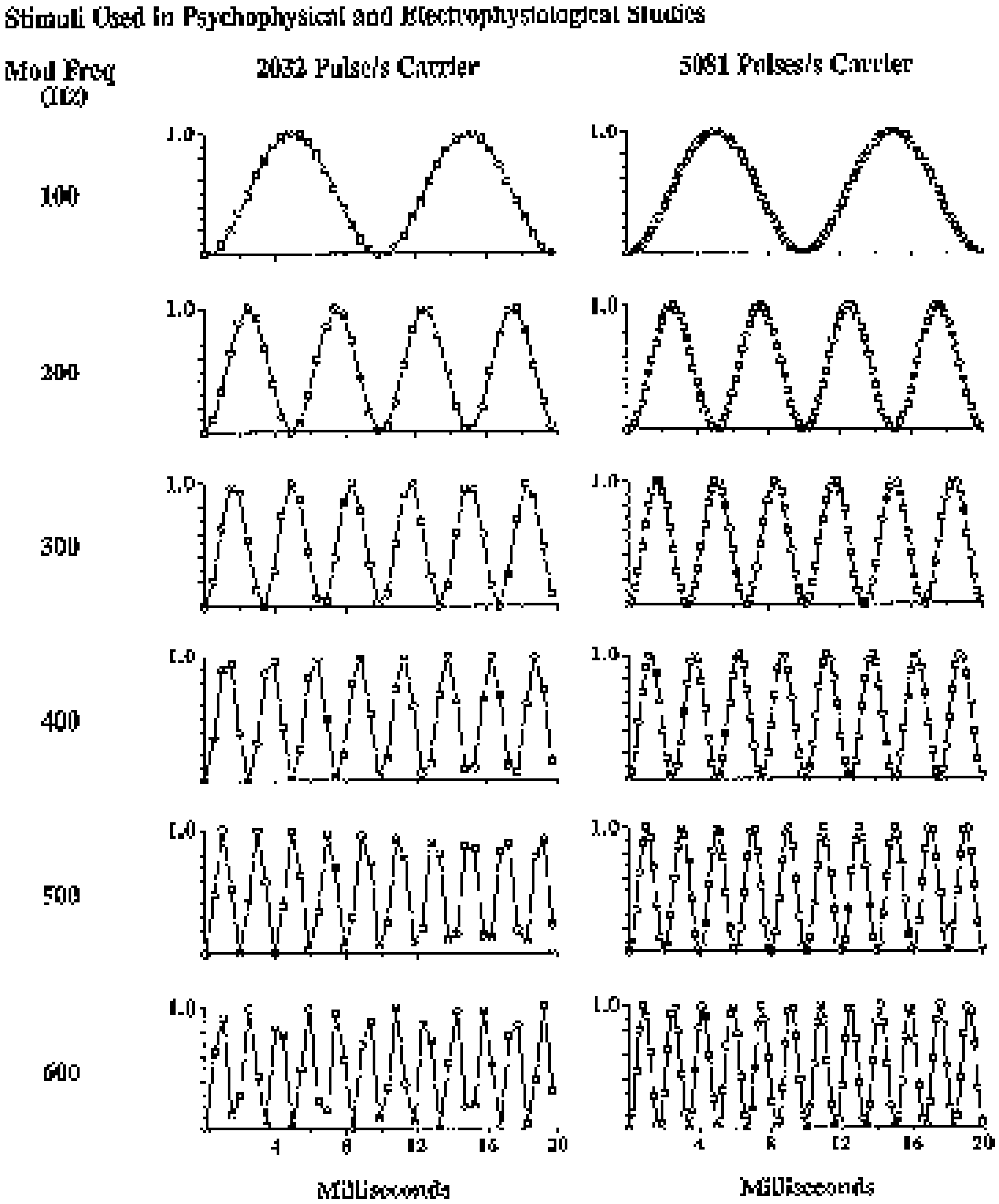


Fig. 5. Normalized amplitudes of stimulus pulses for the SAM pulse trains using the 2032 and 5081 pulses/s carriers. The initial 20 ms of the 200 ms records is shown. Modulation frequencies are indicated in the left column.

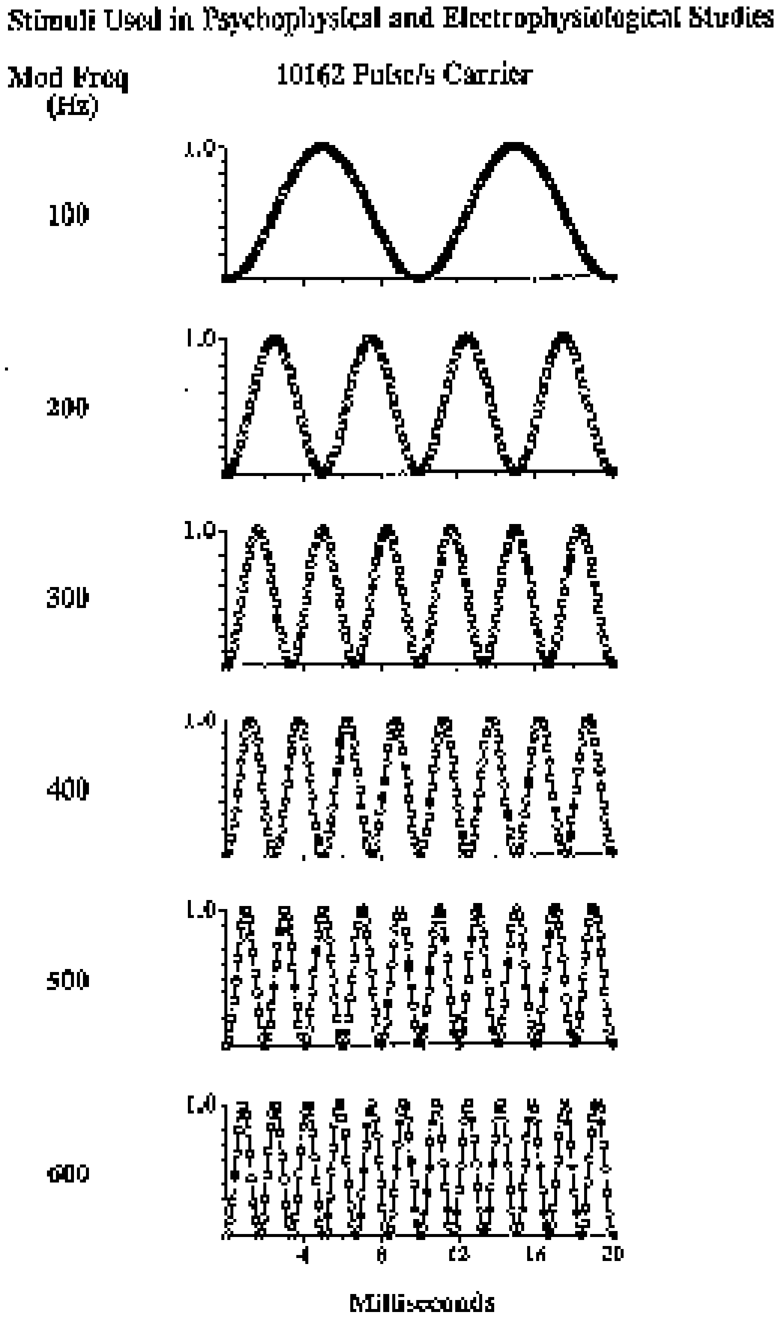


Fig. 6. Normalized amplitudes of stimulus pulses for the SAM pulse trains using the 10162 pulses/s carrier. The initial 20 ms of the 200 ms records is shown. Modulation frequencies are indicated in the left column.

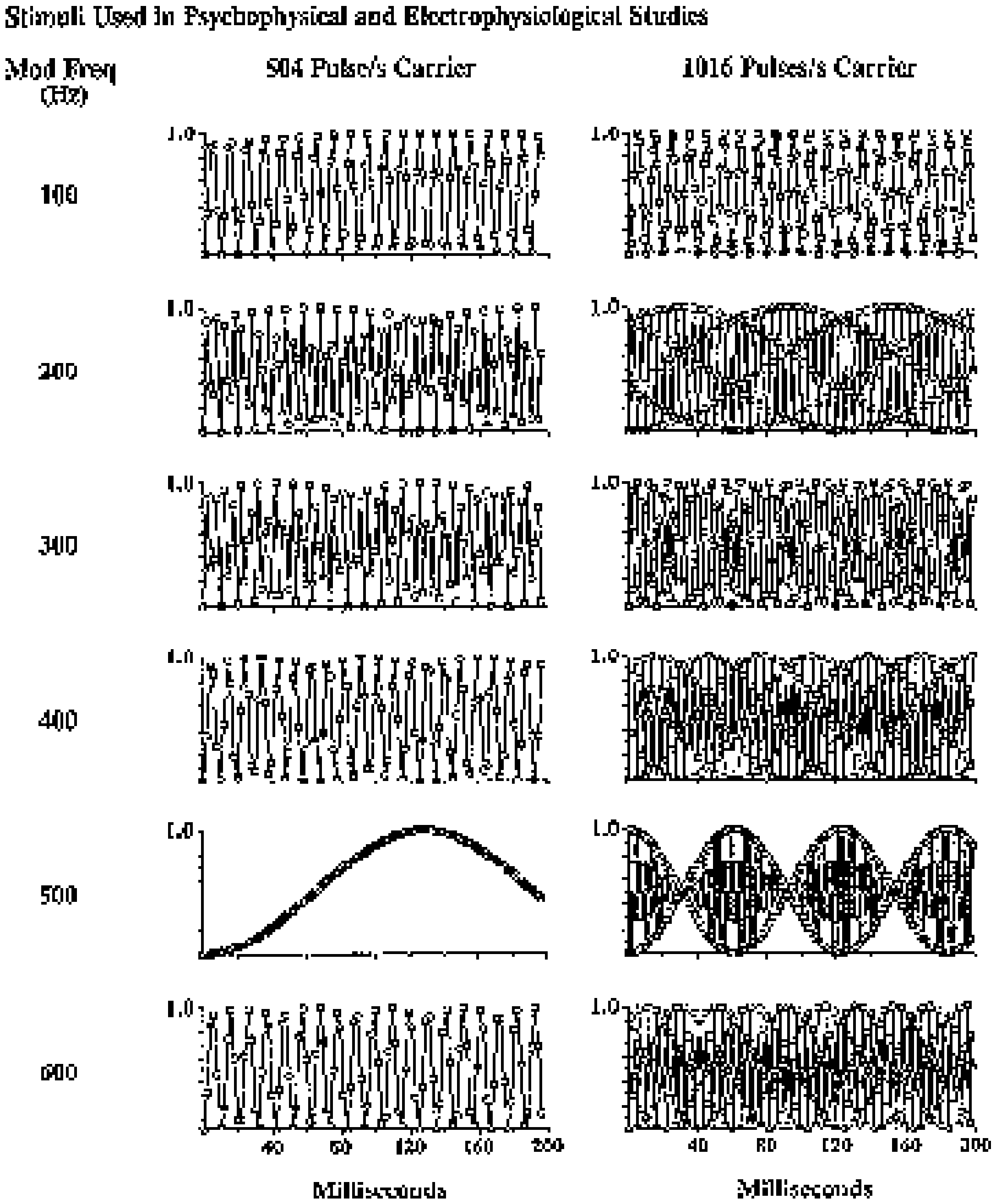


Fig. 7. Normalized amplitudes of stimulus pulses for the SAM pulse trains using the 504 and 1016 pulses/s carriers. The full 200 ms of the records is shown. Modulation frequencies are indicated in the left column.

Hz (period of 62.5 ms) and the amplitudes of sequential pulses alternate between low and high values (Figs. 1 and 4).

Prior recordings of intracochlear EPs for SAM pulse trains

One might expect that sampling artifacts such as those described above might be reflected in patterns of auditory nerve responses to the stimuli. An indication of this was presented in our last quarterly progress report for this project. There we showed patterns of response for SAM pulse trains with the carrier rates of 1016 and 4065 pulses/s, for subject SR2. The modulation frequencies were 100 to 600 Hz in steps of 100 Hz. The carrier amplitude was held constant at 475 µA for both carriers and all modulation frequencies.

The results for the 1016 pulses/s carrier are repeated here in Fig. 8. The left column shows EP magnitudes only (see QPR 7 for a description of the methods used to record and analyze intracochlear EPs) and the right column shows EP magnitudes and stimulus pulse amplitudes. The EP magnitudes are normalized to the maximum EP magnitude across all conditions, and the stimulus pulse amplitudes also are normalized to the maximum pulse amplitude across all conditions. The modulation waveforms for the stimuli are shown in the light lines in the right column.

The patterns of neural responses approximate the modulation waveform for the 100 and 200 Hz modulation conditions. The pattern of response becomes more complicated at the modulation frequency of 300 Hz. At 400 Hz the pattern is both complicated and no longer reflects the period of the modulation waveform. The first interval between major peaks in the response (between pulses 2 and 5) roughly approximates the period, but subsequent intervals are much longer than the period.

As might be expected from the discussion above, patterns of stimuli and responses for the 600 Hz modulation condition are similar to those for the 400 Hz modulation condition. The patterns of response for both conditions are complex. In addition, the interval between principal peaks in the response is the same for the two conditions, about 5 ms. This interval also is observed, of course, for the 200 Hz modulation condition.

Close approximation of the modulation frequency to the Nyquist frequency produces a beat frequency in the patterns of stimulation and responses. This is observed for the 500 Hz modulation condition. Also, the pattern of responses reflects the alternating pattern of pulse amplitudes, for amplitudes that are large enough to elicit a measurable EP.

As described in detail in QPR 7, responses to SAM pulse trains for carrier rates at and below 1016 pulses/s appear to reflect both sampling of the modulation waveform by the carrier pulses and the nonlinear properties of auditory neurons, such as refractory properties. An example of apparent refractory effects may be seen in the panel for the 200 Hz modulation condition. The amplitude of pulse 4 for that condition is greater than the amplitude of pulse 3, and yet the magnitude of the neural response for pulse 4 is much lower than the magnitude of the response for pulse 3.

Three regions of responses can be identified for the 1016 pulses/s carrier. At relatively low modulation frequencies, i.e., 100 and 200 Hz, the responses simply represent the modulation waveform. At somewhat higher modulation frequencies complex patterns of response are observed. Those patterns do not correspond to any details of the modulation waveform and, indeed, at the modulation frequency of 400 Hz do not represent the modulation frequency. Severe sampling artifacts occur as the Nyquist frequency is approximated or exceeded by the modulation frequency.

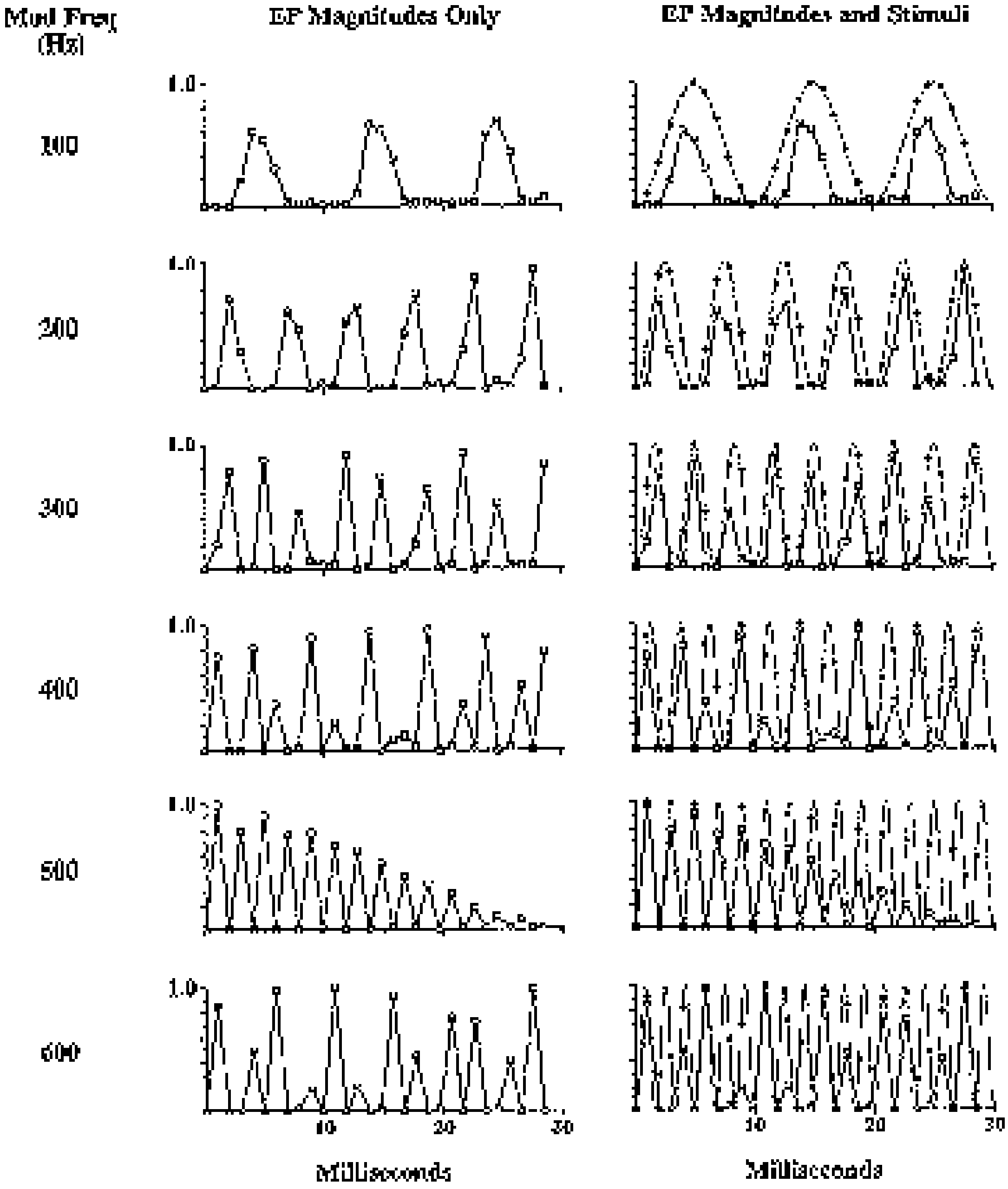


Fig. 8. Evoked potential magnitudes for SAM pulse trains with the carrier rate of 1016 pulses/s. EP magnitudes are normalized to the maximum value across all conditions. The left column shows the modulation frequencies. The right column shows normalized amplitudes of the stimulus pulses in addition to the EP magnitudes. The modulation waveforms for the stimuli are shown by the light lines. Data are from studies with subject SR2. The carrier level for all conditions was 475 µA, and the pulse duration was 33 µs/phase. Stimuli were delivered to intracochlear electrode 3 and recordings of neural responses were made with intracochlear electrode 4.

Results of such artifacts can be seen in the patterns of responses for the 500 and 600 Hz modulation conditions.

Patterns of responses for 1016 and 4065 pulses/s carriers are compared in Fig. 9. Patterns for the 4065 pulses/s carrier show simple representations for all six modulation frequencies (responses for the 4065 pulses/s carrier rate were derived using the subtraction technique described in QPR 7). The patterns of responses follow closely the patterns of stimulation for the modulation frequencies of 400 Hz and lower. The distortions noted before for the 300 and 400 Hz modulation of the 1016 pulses/s carrier are eliminated with the increase in carrier rate to 4065 pulses/s. At the higher modulation frequencies of 500 and 600 Hz, the patterns of responses for the 4065 pulses/s carrier show a shallow alternation between high and low peaks for successive cycles of the modulation waveform. For the 500 Hz condition this alternation may be damped or absent after the initial cycles, as suggested by the pattern of responses for two cycles beginning about 24 ms after the onset of the burst (the subtraction technique allows selection of any interval within a train of stimulus pulses for recording).

The shallow alternation in responses for the 500 and 600 Hz modulation conditions is similar to the alternation observed for unmodulated pulses presented at the rates of 500 and 600 pulses/s (see, e.g., the 604 pulses/s panel in Fig. 4 of QPR 7). The alternation in both cases probably reflects refractory properties of auditory neurons.

Additional aspects of the responses for the 4065 pulses/s carrier are that (a) the peak magnitudes are lower than those for the 1016 pulses/s carrier and (b) the responses from pulse to pulse are smooth and continuous within modulation cycles. These aspects are consistent with the idea that high rate stimuli elicit a more stochastic pattern of responses within and among neurons that low rate stimuli, as described in detail in QPR 7 and elsewhere (Wilson, 1997; Wilson *et al.*, in press).

Psychophysical measures

Findings from measures of intracochlear EPs for SAM and unmodulated pulse trains motivated the present psychophysical experiments. In particular, we wanted to know whether judgments of pitch might be related in some way to the recorded patterns of neural responses for these stimuli.

The subjects and stimuli for these experiments are described above. As noted there, separate experiments were conducted for unmodulated pulse trains and for each of five carrier rates for SAM pulse trains. The amplitudes of the stimuli were adjusted prior to each experiment as necessary to eliminate any differences in loudness across modulation frequency (for SAM pulse trains) or pulse rate (for unmodulated pulse trains) conditions. The subject was instructed to assign a number between 0 and 100 for each stimulus in the experiment according to perceived pitch. Thirty stimuli per condition were presented in random order across the conditions for each experiment for subjects SR3, SR9, SR10, SR15 and SR16. For subject SR2, thirty additional stimuli were presented per condition for the experiments involving the carrier rates of 504 and 1016 pulses/s.

Results for subject SR2 are presented in Fig. 10 and Table 2. Fig. 10 shows the means and standard errors of the means of the judgments for each of the six conditions within the six experiments. Table 2 indicates significant differences in judgments for each of the experiments, as determined from *post hoc* comparisons of the means (using the Tukey criterion, with $p < 0.05$) following a one-way analysis of the variance of the judgments (ANOVA). The initial AVOVA was highly significant for all experiments conducted with SR2 and for all experiments conducted with each of the remaining subjects.

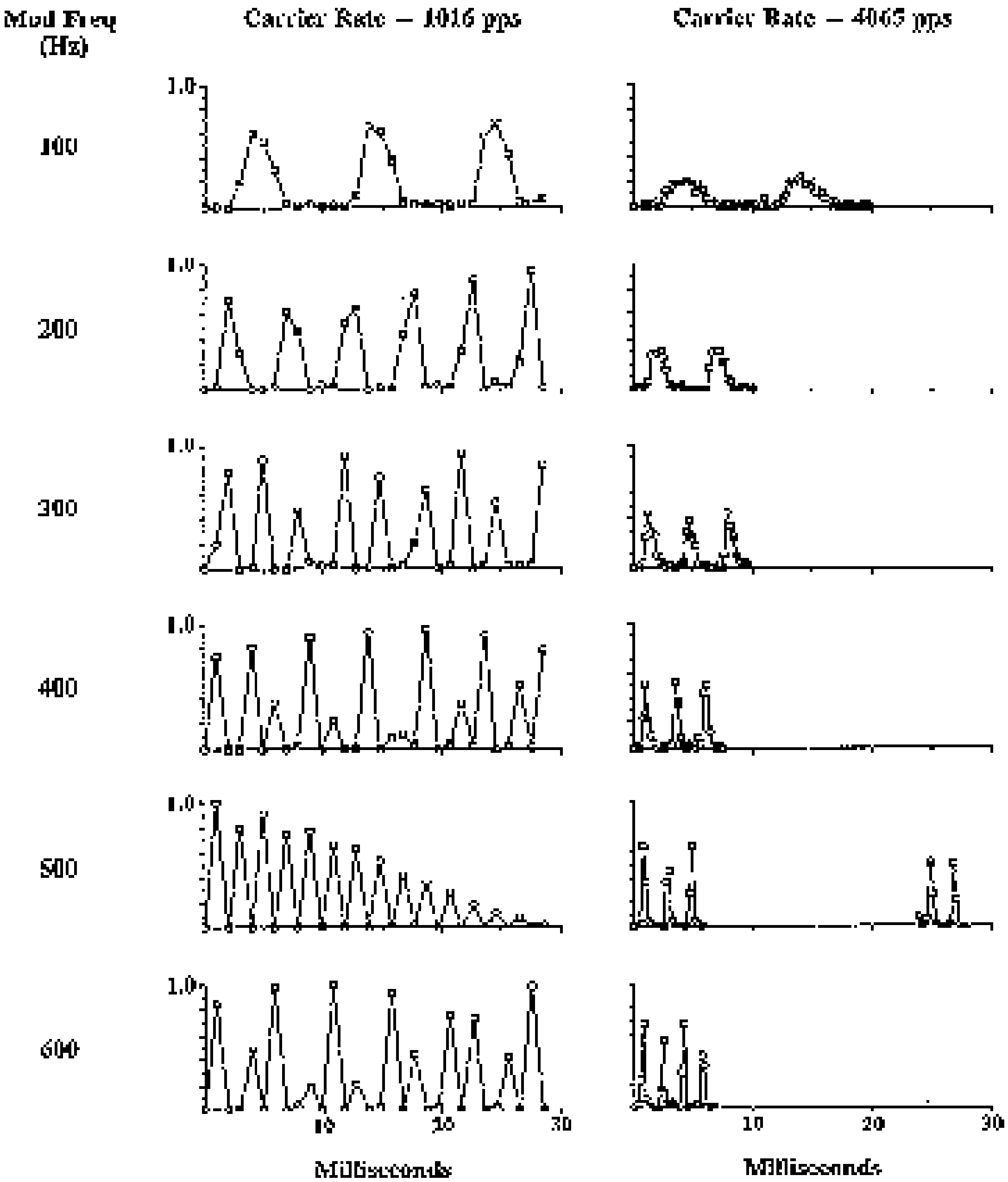


Fig. 9. Evoked potential magnitudes for SAM pulse trains with the carrier rates of 1016 and 4065 pulses/s. EP magnitudes are normalized to the maximum value across all conditions. The left column shows the modulation frequencies. Responses for the high carrier rate conditions were derived using the subtraction technique described in QPR 7 and in Wilson *et al.* (in press). Data are from studies with subject SR2. The carrier level for all conditions was 475 µA, and the pulse duration was 33 µs/phase. Stimuli were delivered to intracochlear electrode 3 and recordings of neural responses were made with intracochlear electrode 4.

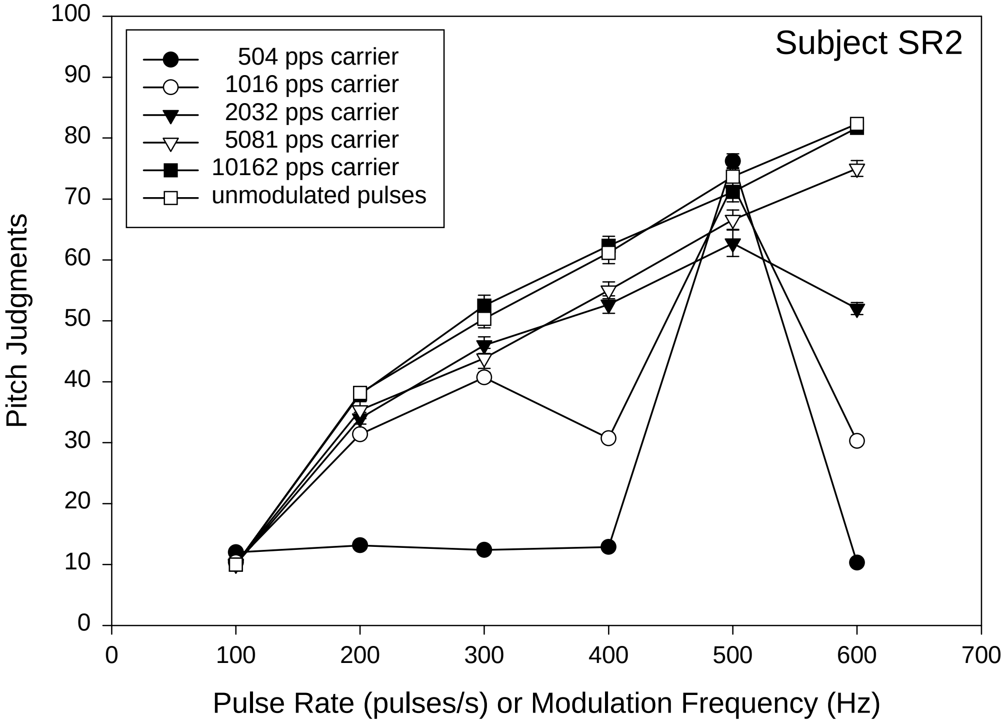


Fig. 10. Scaling results for subject SR2. Bars show standard errors of the mean.

Table 2. Significant differences among conditions for the various stimulus types in the scaling experiment for subject SR2 (see Fig. 10).

Stimulus type	Significant differences among conditions
504 pps carrier	Judgment for 500 Hz mod > judgments for all other mod frequencies Judgments for 200, 300 and 400 Hz mod > judgment for 600 Hz mod
1016 pps carrier	Judgments for all mod frequencies different except 200 *versus* 400, 200 *versus* 600 and 400 *versus* 600 Hz mod
2032 pps carrier	Judgments for all mod frequencies different except 400 *versus* 600 Hz mod
5081 pps carrier	Judgments for all mod frequencies different
10162 pps carrier	Judgments for all mod frequencies different
unmodulated pulses	Judgments for all pulse rates different

As expected from the prior EP recordings, carrier rate influenced the range over which pitch increased monotonically with increases in modulation frequency. For the 1016 pulses/s carrier, for example, increases in modulation frequency beyond 300 Hz did not produce monotonic increases in pitch. In fact, judged pitch is not statistically different for the 200, 400 and 600 Hz modulation conditions. This is consistent with a predominance of 5 ms intervals between major peaks in the neural response patterns for these conditions, as shown in Fig. 8 and the left column of Fig. 9. The judgment for the 500 Hz modulation condition is substantially higher than the judgments for all other conditions. This again is consistent with the pattern of neural responses, which shows peaks separated by 2 ms. The increases in pitch up to the modulation frequency of 300 Hz may correspond to a progressive reduction in the intervals between principal peaks in the neural response patterns as the frequency is increased from 100 to 300 Hz.

Judgments for the 504 pulses/s carrier are highly similar for the modulation frequencies of 100, 200, 300, 400 and 600 Hz. Indeed, the judgments for the first four modulation frequencies are not statistically different. Although this result may seem curious at first sight, recall that these particular combinations of modulation frequency and carrier rate produce a predominance of 10 ms intervals between major peaks in the stimuli (left columns in Figs. 1 and 4). Insofar as the neural response represents these intervals, one would expect a similarity in patterns of auditory nerve activity and perceptual judgments based on that activity across these conditions. (This idea is evaluated quantitatively later in this report.)

The judgment for 500 Hz modulation of the 504 pulses/s carrier shows a large increase in pitch compared with the judgments for the other modulation conditions. In this case, stimulus pulses of similar amplitudes are separated by 2 ms (left columns in Figs. 1 and 4), perhaps producing a much higher pitch than the other conditions, with a predominance of 10 ms intervals between peaks in the stimuli.

Pitch increases monotonically with increases in modulation frequency up to 500 Hz for the 2032 pulses/s condition. Pitch is reduced for the 600 Hz modulation condition, and this judgment does not differ significantly from the judgment for the 400 Hz modulation condition. The 600 Hz condition produces a complicated pattern of stimulus pulses, which may elicit in the nerve a pattern of responses with intervals between principal peaks that are similar to those for the 400 Hz condition.

The findings of reversals in pitch judgments as modulation frequency is increased beyond one fifth to one third of the carrier frequency is consistent with our prior findings (e.g., QPR 7), that the maximum modulation frequency in CIS and other processors should not exceed one fifth to one fourth the carrier frequency for an unambiguous representation of modulation frequencies. We note that Busby *et al.* (1993) have offered this same suggestion based on results from their psychophysical studies with patients using the Nucleus device (and relatively low carrier frequencies).

For the higher carrier rates of 5081 and 10162 pulses/s, and for unmodulated pulses, pitch scales monotonically with increases in modulation frequency or pulse rate, respectively. For the SAM pulse trains, this is consistent with the improved representation of modulation waveforms observed before in the evoked potential recordings involving the carrier rate of 4065 pulses/s (right column in Fig. 9). For unmodulated pulse trains, the monotonic increases in pitch are consistent with a monotonic reduction in the interval between approximately uniform neural responses to the pulses over this range of pulse rates (see left column of Fig. 4 in QPR 7 and later Figures in this report showing neural responses to trains of unmodulated pulses).

An additional aspect of the results for SR2 is that the range of pitch judgments is greatest for the highest carrier rate and for the unmodulated pulses. Also, the curves for the SAM pulse train (with the carrier rate of 10162 pulses/s) and the unmodulated pulses overlie each other and are statistically indistinguishable.

In normal hearing, pitch is perceived at least approximately along a logarithmic scale of frequencies for acoustic stimuli. For example, doublings in frequency produce approximately equal intervals in perceived pitch (corresponding to musical octaves) for comfortably loud sounds and for frequencies below about 4 to 5 kHz. A plot of the data in Fig. 10 with a logarithmic (instead of linear) scale of pulse rates or modulation frequencies shows this also can be observed for cochlear implant subjects like SR2, at least up to 600 pulses/s or 600 Hz, respectively. Such a plot with a logarithmic rate/frequency axis is presented in Fig. 11. Note that the data for the 5081 and 10162 pulses/s carriers, and for the unmodulated pulses, closely approximate straight lines in this semilog plot. There is no evidence of a reduction in slope at the higher rates and frequencies with these types of stimuli for SR2.

In broad terms, use of high carrier rates or unmodulated pulses supports a wide range of pitches for SR2, that increase monotonically with increases in modulation frequency or pulse rate, respectively. In addition, pitch is related to the logarithm of the modulation frequency or pulse rate, as in normal hearing.

Results for the remaining subjects are presented in Figs. 12-16 and the accompanying Tables 3-7. The data are plotted with a logarithmic scale of pulse rates or modulation frequencies, as in Fig. 11 for SR2.

Results for SR3 (Fig. 12 and Table 3) are similar to those described above for SR2. For the 504 pulses/s carrier conditions, relatively low and similar pitches are reported by SR3 for the modulation frequencies of 100, 200, 300, 400 and 600 Hz, as with SR2. Unlike SR2, however, the judgments for the 200 and 300 Hz modulation conditions are significantly higher than the judgments for the 100 and 600 Hz modulation conditions. Also, the judgment for the 300 Hz modulation condition is higher than the judgment for the 400 Hz modulation condition. Like SR2, the judgment for the 500 Hz modulation condition is significantly (and substantially) higher than the judgments for all other modulation conditions.

The patterns of judgments for the 1016 pulses/s carrier conditions are identical for SR2 and SR3, although the overall range of pitches reported by SR3 is less than the overall range reported by SR2 for this and all other types of stimuli.

The patterns of judgments for the 2032 pulses/s carrier conditions are slightly different for the two subjects. Both subjects show monotonic increases in pitch up to the modulation frequency of 500 Hz, and then a decrement in pitch with the further increase in modulation frequency to 600 Hz. The judgment at 600 Hz is not statistically different from the judgment at 400 Hz for subject SR2, whereas the judgment at 600 Hz is significantly lower than the judgment at 400 Hz for subject SR3. For SR3, the judgment at 300 Hz is the same as the judgment at 600 Hz.

Monotonic increases in pitch are observed for SR3 for the carrier rates of 5081 and 10162 pulses/s, and for unmodulated pulse trains, as with SR2. However, for SR3 not all of the adjacent modulation frequencies or pulse rates (for the unmodulated pulse trains) are significantly different. Use of each

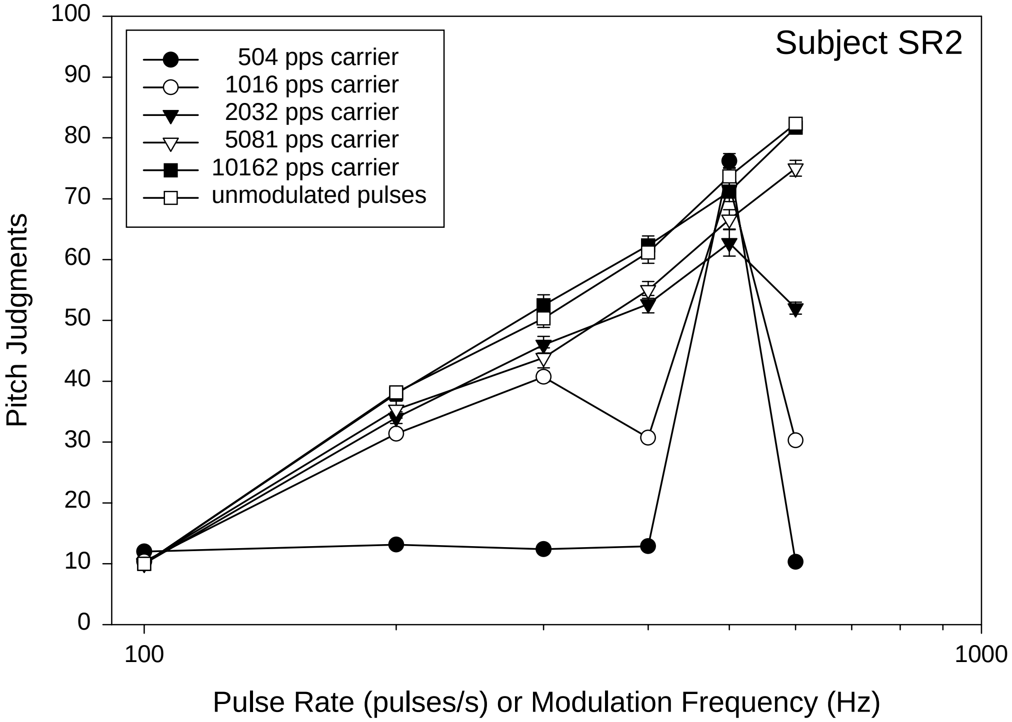


Fig. 11. Scaling results for SR2, plotted along a logarithmic axis of pulse rate or modulation frequency. Bars show standard errors of the mean.

of these stimulus types appears to produce an asymptote in judgments at high modulation frequencies or pulse rates. In particular, the judgments for the 500 and 600 Hz modulation conditions are not significantly different for either the 5081 or 10162 pulses/s carrier, and similarly the judgments for the 500 and 600 pulses/s conditions are not significantly different for the unmodulated pulse trains. Also, the judgments for the 300 and 400 Hz modulation conditions are statistically the same for the 5081 pulses/s carrier, and the judgments for the 300 and 400 pulses/s conditions are statistically the same for the unmodulated pulse trains.

Another difference in the patterns of results between SR2 and SR3 is that all judgments for the lowest modulation frequency for SAM pulse trains, and for the lowest pulse rate for unmodulated pulse trains, are very similar for SR2 but dissimilar for SR3. The judgments for SR3 become progressively lower for the 100 Hz modulation condition as the carrier rate is increased for SAM pulse trains. The judgment for the 100 pulses/s conditions for the unmodulated pulse trains approximates the above judgments for the 5081 and 10162 pulses/s carriers. The greatest overall range of pitch judgments is produced with SAM pulse trains using the carrier rate of 10162 pulses/s.

Findings for SR9 (Fig. 13 and Table 4), one of the two subjects with very poor speech reception scores, are quite different from those described above for “superstar” subject SR2 and excellent-performance subject SR3. Although SR9 shows a pattern of results that is similar to the patterns for SR2 and SR3 for SAM pulse trains with the 504 pulses/s carrier, patterns of results for the other types of stimuli show a high similarity of pitch judgments for all modulation frequencies and pulse

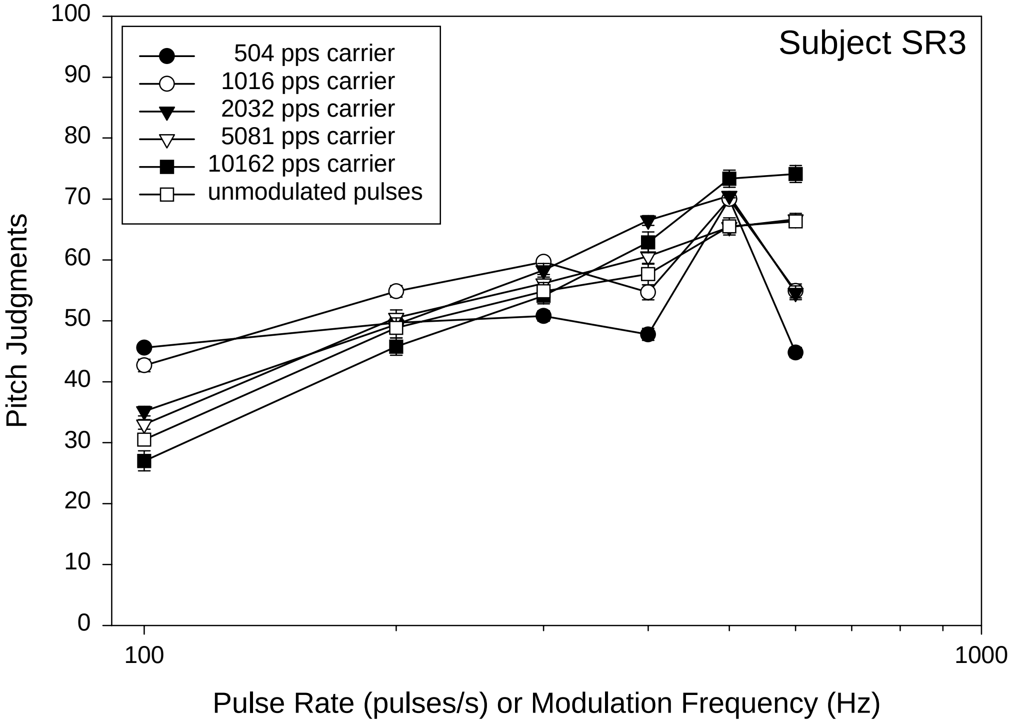


Fig. 12. Scaling results for subject SR3. Bars show standard errors of the mean.

Table 3. Significant differences among conditions for the various stimulus types in the scaling experiment for subject SR3 (see Fig. 12).

Stimulus type	Significant differences among conditions
504 pps carrier	Judgment for 500 Hz mod > judgments for all other mod frequencies Judgments for 200 and 300 Hz mod > judgments for 100 and 600 Hz mod Judgment for 300 Hz mod > judgment for 400 Hz mod
1016 pps carrier	Judgments for all mod frequencies different except 200 *versus* 400, 200 *versus* 600 and 400 *versus* 600 Hz mod
2032 pps carrier	Judgments for all mod frequencies different except 300 *versus* 600 Hz mod
5081 pps carrier	Judgments for all mod frequencies different except 300 *versus* 400 and 500 *versus* 600 Hz mod
10162 pps carrier	Judgments for all mod frequencies different except 500 *versus* 600 Hz mod
unmodulated pulses	Judgments for all pulse rates different except 300 *versus* 400 and 500 *versus* 600 pps

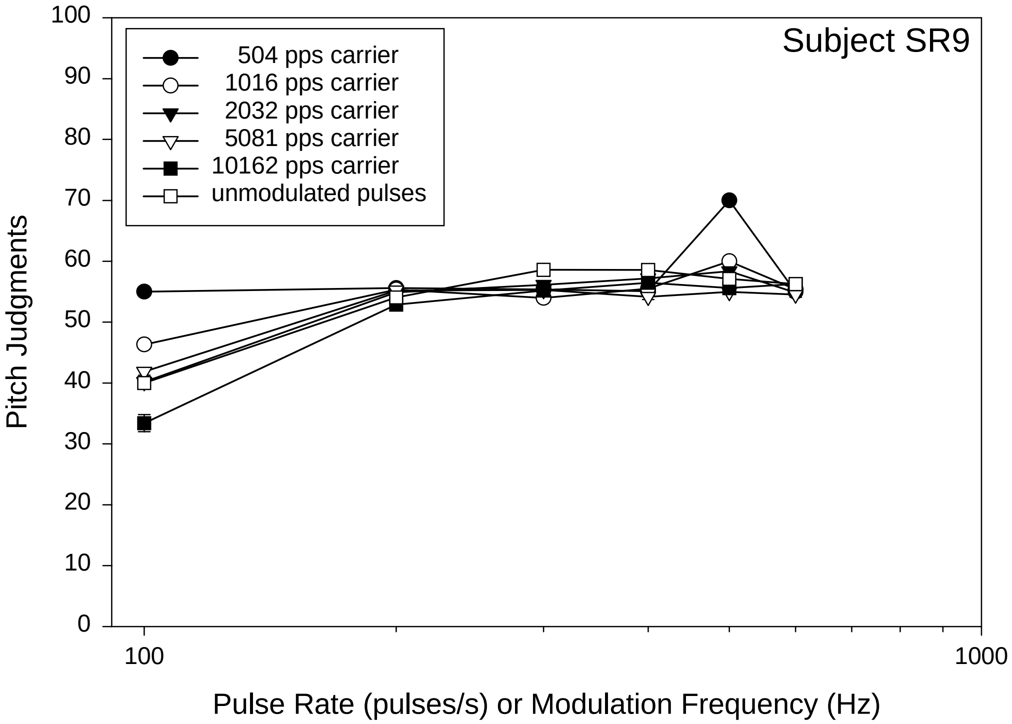


Fig. 13. Scaling results for subject SR9. Bars show standard errors of the mean.

Table 4. Significant differences among conditions for the various stimulus types in the scaling experiment for subject SR9 (see Fig. 13).

Stimulus type	Significant differences among conditions
504 pps carrier	Judgment for 500 Hz mod > judgments for all other mod frequencies Judgment for 200 Hz mod > judgments for 100 and 600 Hz mod
1016 pps carrier	Judgment for 500 Hz mod > judgments for all other mod frequencies Judgments for 200, 300, 400 and 600 Hz mod > judgment for 100 Hz mod Judgment for 400 Hz mod > judgment for 300 Hz mod
2032 pps carrier	Judgment for 500 Hz mod > judgments for 100, 200, 300 and 600 Hz mod Judgments for 200, 300, 400 and 600 Hz mod > judgment for 100 Hz mod Judgment for 400 Hz mod > judgments for 200 and 600 Hz mod
5081 pps carrier	Judgments for 200, 300, 400, 500 and 600 Hz mod > judgment for 100 Hz mod
10162 pps carrier	Judgments for 200, 300, 400, 500 and 600 Hz mod > judgment for 100 Hz mod Judgments for 400 and 600 Hz mod > judgment for 200 Hz mod
unmodulated pulses	Judgments for all pulse rates different except 300 *versus* 400, 300 *versus* 500, 400 *versus* 500 and 500 *versus* 600 pps

rates above 200 Hz or 200 pulses/s, respectively. Pitch does not increase with increases in modulation frequency from 200 to 600 Hz for the 5081 and 10162 pulses/s carriers, nor does it increase with increases in pulse rate from 300 to 600 pulses/s for the unmodulated pulse trains. In fact, the judgment for 600 pulses/s is significantly lower than the judgments for 300 and 400 pulses/s for the unmodulated pulse trains.

Although the judgments for the 500 Hz modulation condition with the 1016 pulses/s carrier is higher than the judgments for all other modulation conditions, as with SR2 and SR3, judgments for the conditions between and including 200 to 400 Hz modulation do not show monotonic increases in pitch like the other two subjects.

The peaks in judgments for the 500 Hz modulation conditions for the 504 and 1016 pulses/s carrier do not demonstrate that SR9 can perceive a 500 Hz signal as such, but instead merely indicate that she can distinguish that modulation frequency from the rest, perhaps through the gross sampling artifacts produced with 500 Hz modulation of these carriers (see Figs. 1, 4 and 7).

One similarity between patterns of results for SR9 and SR3 is the progressive reduction in pitch judgments for the 100 Hz modulation condition with increases in carrier rate. Also, like SR3, the judgment made by SR9 for the 100 pulses/s condition with unmodulated pulse trains is relatively low, again between the judgments for 100 Hz modulation of the 5081 and 10162 pulses/s carriers for SAM pulse trains. The overall range of pitch judgments is greatest with the SAM pulse trains using the 10162 pulses/s carrier for both subjects.

The overall picture presented by the findings for SR9 is one of a general saturation (or even reversal) in judgments as modulation frequency or pulse rate is increased beyond 200 Hz or 200 pulses/s, respectively. In addition, SR9 hears 500 Hz modulation of low-rate carriers as higher in pitch than other modulation conditions. The range of pitch judgments exhibited by SR9 is substantially lower than the ranges exhibited by SR2 and SR3.

Results for subject SR10 (Fig. 14 and Table 5) are intermediate to those for SR2 and SR3 at one extreme, and for SR9 at the other extreme. The judgments for SR10 also are somewhat more variable than the judgments for these other three subjects.

Like the other three subjects, SR10 shows a peak in judgments at the modulation frequency of 500 Hz for the 504 and 1016 pulses/s carriers. Also like the other subjects, SR10 shows a similarity of judgments for 100, 200, 300, 400 and 600 Hz modulation of the 504 pulses/s carrier. In fact, judgments for these various modulation frequencies are not statistically different for SR10. Like SR9, pitch does not increase with increases in modulation frequency between 200 and 400 Hz for the 1016 pulses/s carrier. Pitch increases monotonically over this range and up to 500 Hz for the carrier rate of 2032 pulses/s, as with SR2 and SR3. However, the difference in judgments for the 200 and 300 Hz modulation conditions is not significant for SR10. As with the other three subjects, pitch for 600 Hz modulation of the 2032 pulses/s carrier is significantly lower than the pitch for 500 Hz modulation of that carrier. Like SR3 and SR9, the judgment for 400 Hz modulation of the 2032 pulses/s carrier also is higher than the judgment for the 600 Hz modulation condition. That is, a broad peak in pitch judgments is observed for SR3 and SR10 encompassing 400 and 500 Hz modulation of the 2032 pulses/s carrier, whereas a sharp peak at 500 only is observed for SR2. A broad increment in judgments also is observed for SR9 encompassing 300 to 500 Hz modulation of the 2032 pulses/s carrier, although this relatively small increment hardly could be characterized as a "peak."

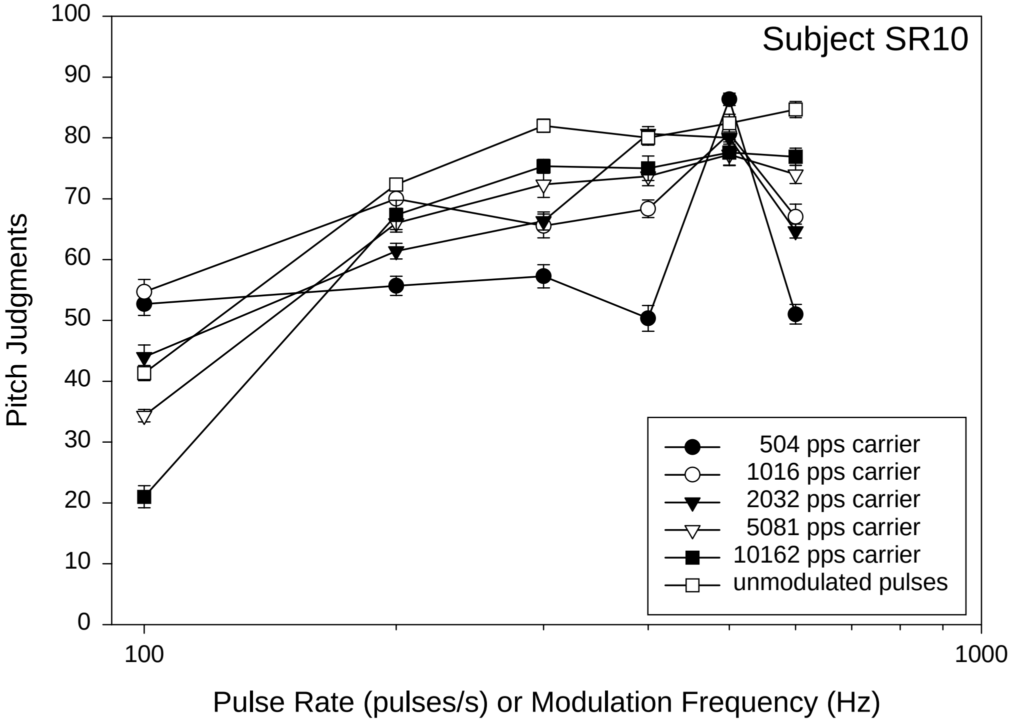


Fig. 14. Scaling results for subject SR10. Bars show standard errors of the mean.

Table 5. Significant differences among conditions for the various stimulus types in the scaling experiment for subject SR10 (see Fig. 14).

Stimulus type	Significant differences among conditions
504 pps carrier	Judgment for 500 Hz mod > judgments for all other mod frequencies
1016 pps carrier	Judgment for 500 Hz mod > judgments for all other mod frequencies
	Judgments for 200, 300, 400 and 600 Hz mod > judgment for 100 Hz mod
2032 pps carrier	Judgments for all mod frequencies different except for 200 *versus* 300, 200 *versus* 600, 300 *versus* 600 and 400 *versus* 500 Hz mod
5081 pps carrier	Judgments for 200, 300, 400, 500 and 600 Hz mod > judgment for 100 Hz mod
	Judgments for 400, 500 and 600 Hz mod > judgment for 200 Hz mod
10162 pps carrier	Judgments for 200, 300, 400, 500 and 600 Hz mod > judgment for 100 Hz mod
	Judgments for 300, 400, 500 and 600 Hz mod > judgment for 200 Hz mod
unmodulated pulses	Judgments for 200, 300, 400, 500 and 600 pps > judgment for 100 pps
	Judgments for 300, 400, 500 and 600 pps > judgment for 200 pps

For SR10, pitch increases with increases in modulation frequency up to 200 Hz for the carrier rates of 2032 and 5081 pulses/s, and up to 300 Hz for the carrier rate of 10162 pulses/s. Further increases in modulation frequency do not produce significant increases in pitch, except for the 5081 pulses/s carrier, where pitch for the 400, 500 and 600 Hz modulation conditions is higher than that for the 200 Hz condition. The pattern of results for unmodulated pulse trains is similar to the pattern for SAM pulse trains using the 10162 pulses/s carrier. Both patterns show increases in pitch up to 300 pulses/s or 300 Hz, respectively, and a saturation of judgments thereafter.

As with subjects SR3 and SR9, the greatest range of pitch judgments is produced for SR10 with SAM pulse trains using the 10162 pulses/s carrier. Also like SR3 and SR9, increases in carrier rate (at least over the range from 1016 to 10162 pulses/s) produce progressive reductions in pitch for the 100 Hz modulation conditions. Pitch for the 100 pulses/s condition using unmodulated pulse trains falls in the range of pitches for the 100 Hz modulation conditions using SAM pulse trains, as in the results for SR3 and SR9.

As indicated above, the studies with SR15 did not include the 10162 pulses/s carrier or unmodulated pulses. However, her results for the remaining types of stimuli (Fig. 15 and Table 6) are similar in most respects to those of SR9, another subject with extremely low levels of speech reception performance. Like SR9, pitch generally does not increase for SR15 with increases in modulation frequency above 200 Hz. The one exception is a significant increase for 500 Hz modulation of the 504 and 1016 pulses/s carriers, also observed for SR9 and all other subjects (including SR16, see below).

The variability of judgments for SR15 is substantially higher than that for all other subjects except SR10. SR15 does not enjoy good access to temporal information in these stimuli even for the modulation frequency of 100 Hz.

Results for SR16 (Fig. 16 and Table 7) are similar in various respects to the results for SR2, SR3 and SR10, all subjects with at least moderate levels of speech reception performance using a CIS processor. The pattern of the results for the 504 pulses/s carrier is either exactly the same or essentially the same as the patterns for all other subjects, including SR2, SR3 and SR10. For the 1016 pulses/s carrier, results for SR16 are similar to those for SR10. Pitch increases for both subjects with an increase in the modulation frequency from 100 to 200 Hz. A further increase in modulation frequency to 300 Hz produces a significant decrement in pitch for SR16 and no change in pitch for SR10 (the mean at 300 Hz is lower than the mean of 200 Hz for SR10, but the difference in means is not significant). Like SR10 and all other subjects, SR16 shows a peak in judgments at 500 Hz modulation of the 1016 pulses/s carrier, as noted above.

Results for SR16 using the 2032 pulses/s carrier are similar to those of SR3 and SR10 using that carrier. Pitch increases monotonically up to the modulation frequency of 400 Hz for these subjects and carrier rate. A broad peak in judgments is observed across the modulation frequencies of 400 and 500 Hz. The further increase in modulation frequency to 600 Hz produces a significant decrement in pitch for these and all other subjects except SR15 (no difference in pitch is observed for SR15).

At the higher carrier rates of 5081 and 10162 pulses/s, results for SR16 show monotonic increases in pitch with increases in modulation frequency. However, not all of the increases in pitch are significant. For the 5081 pulses/s carrier, the differences between 300 and 400 Hz modulation, and

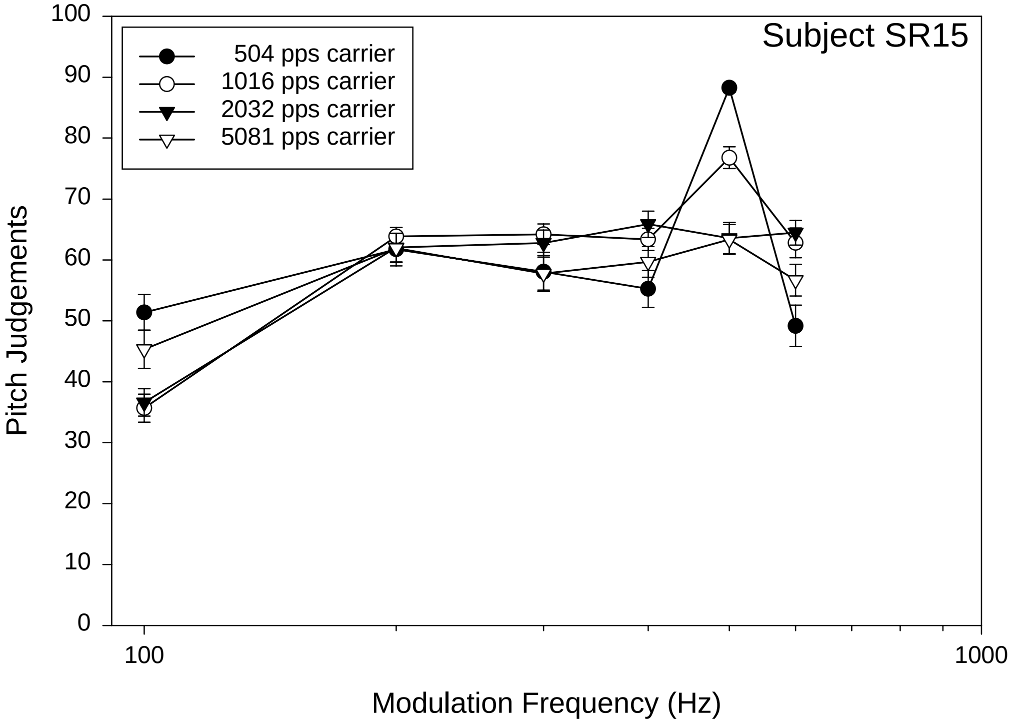


Fig. 15. Scaling results for subject SR15. Bars show standard errors of the mean.

Table 6. Significant differences among conditions for the various stimulus types in the scaling experiment for subject SR15 (see Fig. 15).

Stimulus type	Significant differences among conditions
504 pps carrier	Judgment for 500 Hz mod > judgments for all other mod frequencies Judgment for 200 Hz mod > judgment for 600 Hz mod
1016 pps carrier	Judgment for 500 Hz mod > judgments for all other mod frequencies Judgments for 200, 300, 400 and 600 Hz mod > judgment for 100 Hz mod
2032 pps carrier	Judgments for 200, 300, 400, 500 and 600 Hz mod > judgment for 100 Hz mod
5081 pps carrier	Judgments for 200, 300, 400, 500 and 600 Hz mod > judgment for 100 Hz mod

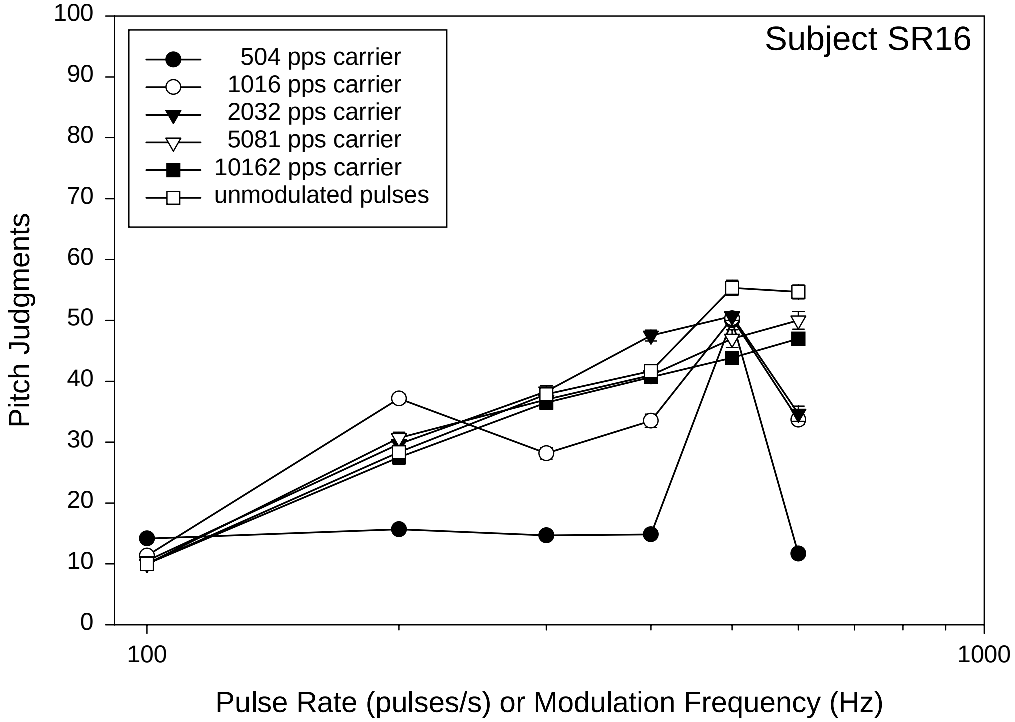


Fig. 16. Scaling results for subject SR16. Bars show standard errors of the mean.

Table 7. Significant differences among conditions for the various stimulus types in the scaling experiment for subject SR16 (see Fig. 16).

Stimulus type	Significant differences among conditions
504 pps carrier	Judgment for 500 Hz mod > judgments for all other mod frequencies Judgments for 100, 200, 300 and 400 Hz mod > judgment for 600 Hz mod
1016 pps carrier	Judgments for all mod frequencies different except for 400 *versus* 600 Hz mod
2032 pps carrier	Judgments for all mod frequencies different except for 300 *versus* 600 and 400 *versus* 500 Hz mod
5081 pps carrier	Judgments for all mod frequencies different except for 300 *versus* 400 and 500 *versus* 600 Hz mod
10162 pps carrier	Judgments for all mod frequencies different except for 400 *versus* 500 and 500 *versus* 600 Hz mod
unmodulated pulses	Judgments for all pulse rates different except for 300 *versus* 400 and 500 *versus* 600 pps

between 500 and 600 Hz modulation, are not significant. For the 10162 pulses/s carrier, the differences between 400 and 500 Hz modulation, and between 500 and 600 Hz modulation, also are not significant.

For unmodulated pulse trains, pitch increases monotonically for SR16 with increases in pulse rate up to 500 pulses/s. The further increase to 600 pulses/s does not produce an increase in pitch. Also, the difference in means for the 300 and 400 pulses/s conditions is not significant.

The overall picture for SR16 is one of reasonably good access to modulation frequencies for carrier rates of 5081 and 10162 pulses/s, and to pulse rates up to 500 pulses/s for the unmodulated pulse trains. Access to modulation frequencies at and below 500 Hz also is reasonably good using the carrier rate of 2032 pulses/s. The overall ranges of pitch judgments are similar across the different types of stimuli for SR16.

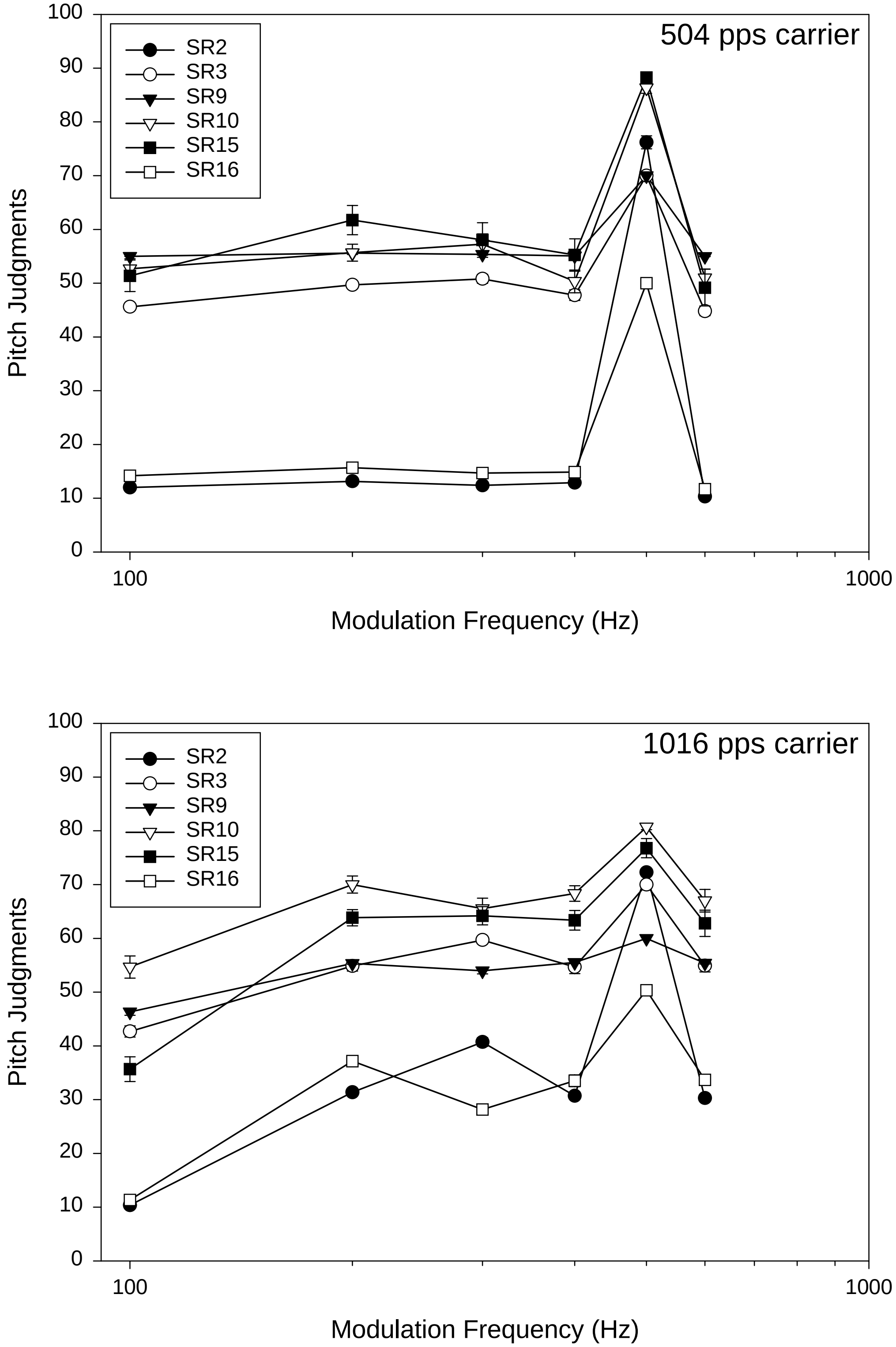
Like SR2, judgments for the 100 Hz modulation conditions for SAM pulse trains, and for the 100 pulses/s condition for the unmodulated pulse trains, are indistinguishable in SR16’s results.

Many of these similarities and differences among results for the different subjects can be more easily seen in the plots of Figs. 17-22, which show results across subjects for each of the various types of stimuli. As shown in Fig. 17, patterns of responses for SAM pulse trains with the 504 pulses/s carrier are highly similar across subjects. All subjects show a peak in pitch judgments for the 500 Hz modulation condition. In addition, all subjects report approximately the same pitches for the remaining modulation conditions. Some subjects report somewhat higher pitches for the 200 and 300 Hz modulation conditions compared to their reports for the 100, 400 and 600 Hz conditions. In some cases, the judgment for the 600 Hz condition is lower than one or more of the judgments for the 100, 200, 300 and 400 Hz conditions.

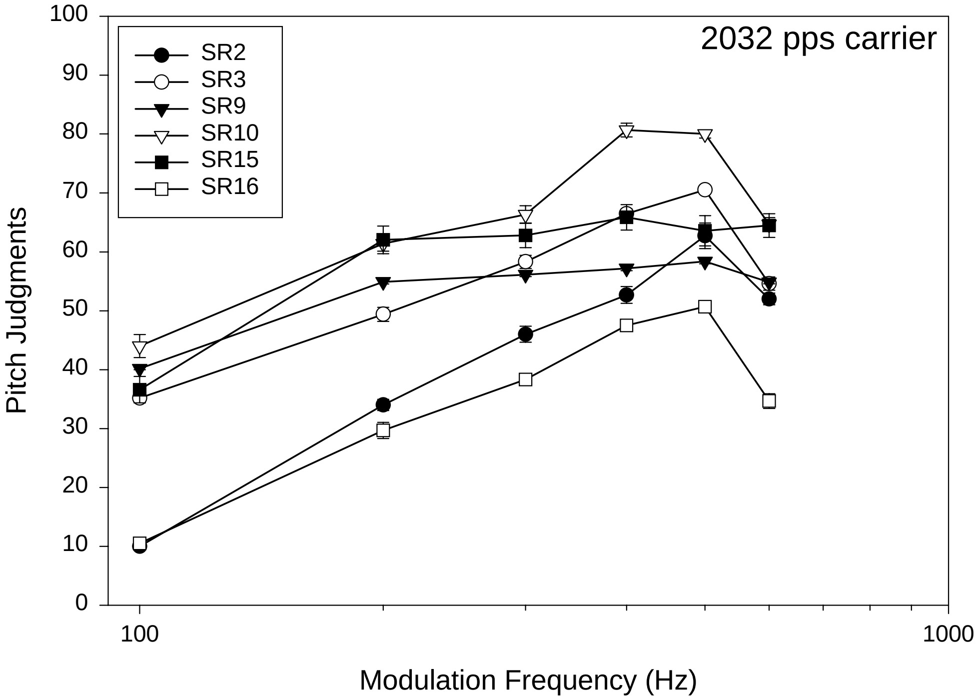
With an increase in the carrier rate to 1016 pulses/s (Fig. 18), all subjects judge the 200 Hz modulation condition to be higher in pitch than the 100 Hz condition. In addition, all subjects show a peak in judgments for the 500 Hz modulation condition, as above with the 504 pulses/s carrier. Judgments for the 300 Hz modulation condition with the 1016 pulses/s carrier are sometimes higher and sometimes lower than the judgments for the neighboring modulation frequencies. The judgments are significantly higher for subjects SR2 and SR3, whereas the judgments are significantly lower for subjects SR9 (comparison between 300 and 400 Hz modulation conditions only) and SR16. The judgments for the 200, 400 and 600 Hz conditions are similar for all subjects.

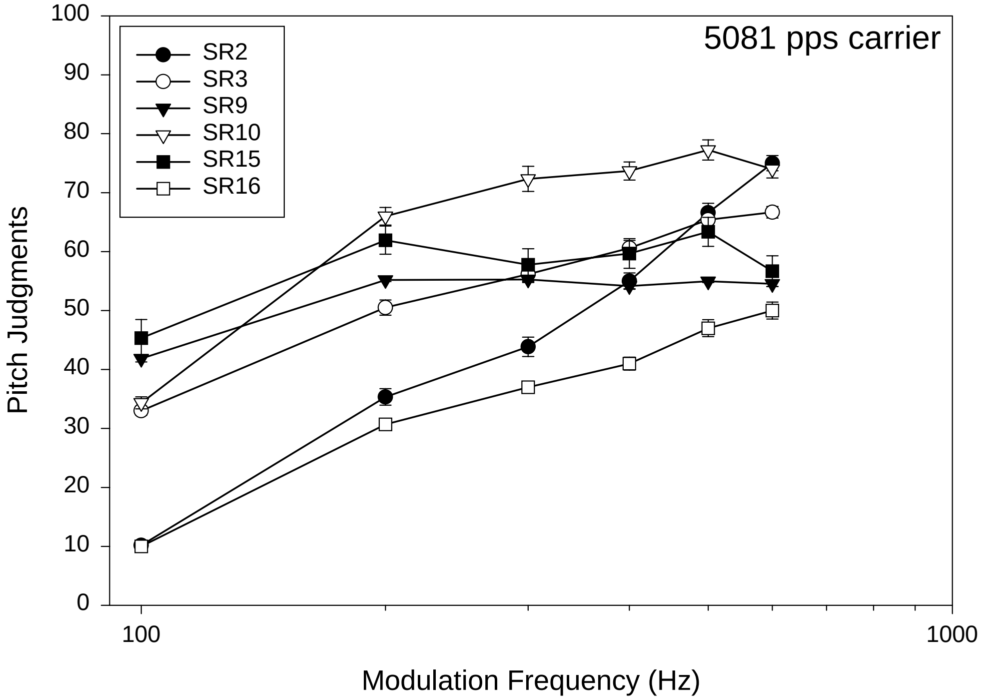
A further increase in carrier rate to 2032 pulses/s (Fig. 19) extends the range over which pitch increases monotonically with increases in modulation frequency for four of the six subjects. In addition, all subjects except SR15 show a peak in judgments at either the modulation frequency of 500 Hz (subjects SR2 and SR3) or across the modulation frequencies of 400 and 500 Hz (subjects SR9, SR10 and SR16).

For the 5081 pulses/s carriers (Fig. 20), judgments increase monotonically over the entire range of modulation frequencies for subjects SR2, SR3 and SR16, although the differences in judgments for 300 versus 400 Hz modulation, and for 500 versus 600 Hz modulation, are not significant for SR3 and SR16. Subject SR10 also shows increases in pitch over much of the range of modulation frequencies with the 5081 pulses/s carrier. His judgments at the modulation frequencies of 200 through 600 Hz are higher than his judgment for the 100 Hz condition, and his judgments at the modulation frequencies of 400 through 600 Hz are higher than his judgment for the 200 Hz

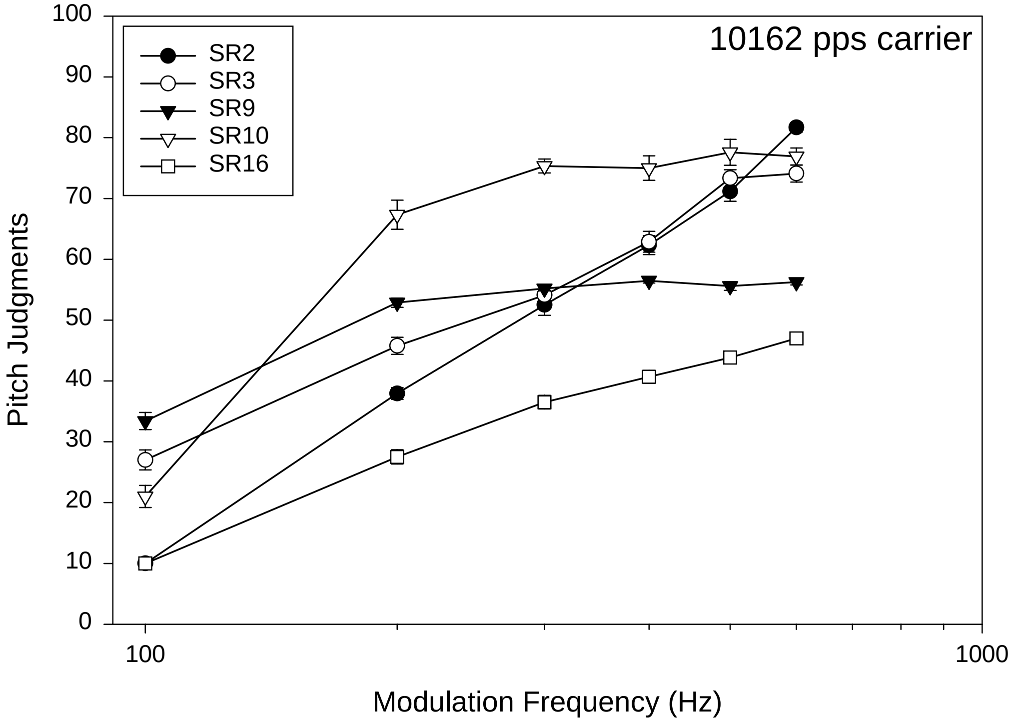


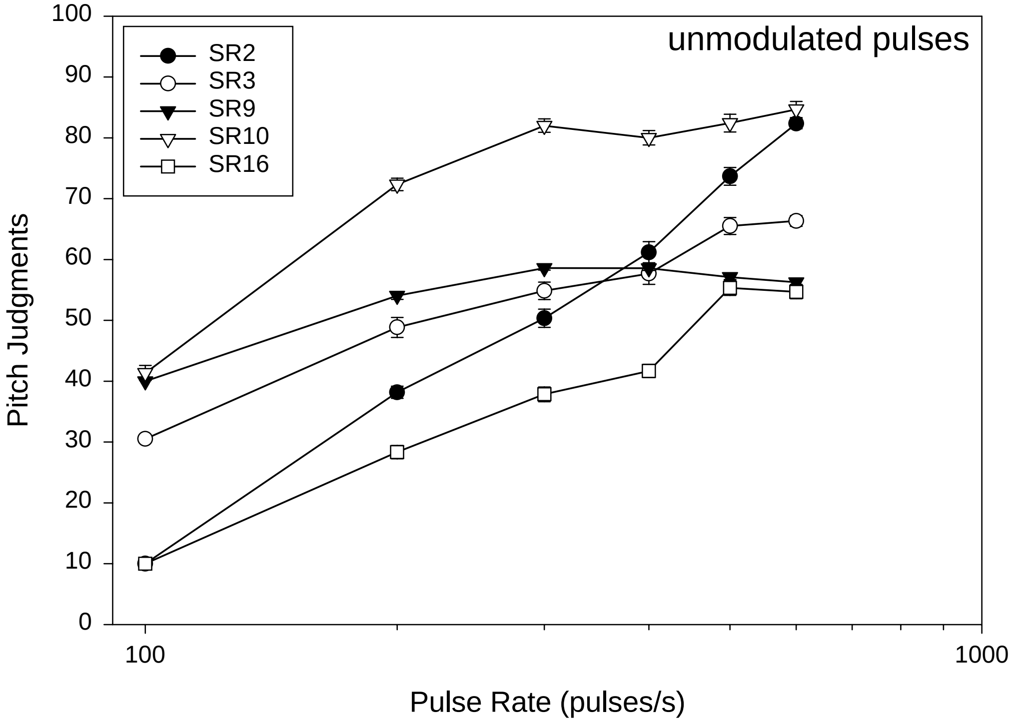
Figs. 17 and 18. Scaling results for the 504 pulses/s carrier conditions (Fig. 17, top) and for the 1016 pulses/s carrier conditions (Fig. 18). Bars show standard errors of the mean.





Figs. 19 and 20. Scaling results for the 2032 pulses/s carrier conditions (Fig. 19, top) and for the 5081 pulses/s carrier conditions (Fig. 20). Bars show standard errors of the mean.





Figs. 21 and 22. Scaling results for the 10162 pulses/s carrier conditions (Fig. 21, top) and for the unmodulated pulse train conditions (Fig. 22). Bars show standard errors of the mean.

condition. Judgments for all modulation frequencies between 200 and 600 Hz are not statistically different for subjects SR9 and SR15. However, judgments at those modulation frequencies are higher than the judgment for the 100 Hz modulation condition for both subjects.

The increase in carrier rate to 10162 pulses/s (Fig. 21) generally increases the range over which pitches are reported. Also, differences in pitch between adjacent modulation frequencies that are not significant with the 5081 pulses/s carrier become significant with the 10162 pulses/s carrier. An example is the difference in judgments for SR3 between the modulation frequencies of 300 versus 400 Hz. That difference is not significant for the 5081 pulses/s carrier, whereas the difference is significant with the 10162 pulses/s carrier. In addition, the difference in judgments between 200 versus 300 Hz becomes significant for SR10 with the increase in carrier rate to 10162 pulses/s. Results for SR9 still indicate a saturation in judgments beyond the modulation frequency of 200 Hz. However, with the 10162 pulses/s carrier the judgments for the 400 and 600 Hz modulation conditions are (just) statistically higher than the judgment for the 200 Hz modulation condition. SR15 was not tested with the 10162 pulses/s carrier, as noted above.

Results for the unmodulated pulse trains (Fig. 22) are similar in many respects to those for the SAM pulse trains with the 10162 pulses/s carrier. The overall range of pitch judgments is wide for both types of stimuli. However, increases in pitch with increases in modulation frequency for the 10162 pulses/s carrier appear to be somewhat more uniform than the increases in pitch with increases in pulse rate for the unmodulated pulse trains. An example is the relatively large “jumps” in pitch with increases in pulse rate from 400 to 500/s for subjects SR3 and SR16 using the unmodulated pulse trains. Such relatively large increases in pitch are not observed for the same subjects using the SAM pulse trains with the carrier rate of 10162 pulses/s.

In all, the widest range of pitches, and the largest number of distinct increases in pitch with increases in modulation frequency or pulse rate, are supported with use of SAM pulse trains with the highest carrier rate tested or with use of unmodulated pulse trains, respectively. The uniformity and monotonicity of judgments is somewhat better with the SAM pulse trains.

Electrophysiological measures

To evaluate possible relationships between the psychophysical findings reviewed above and patterns of auditory nerve activity, we first measured auditory nerve responses to the same stimuli used in the psychophysical experiments with subjects SR2, SR3, SR9 and SR10 (measures with subjects SR15 and SR16 are planned for early 1998). Once we had the measures of auditory nerve responses, we then could compare features of the responses with the findings from the psychophysical experiments.

Recordings were made for all stimuli in the psychophysical experiments that did not require use of the subtraction procedure described in QPR 7 (see Fig. 3 and the associated discussion in QPR 7). Use of the subtraction procedure for the present studies would have required N recordings for the N pulses in each of the 200 ms trains of pulses for all carrier rates greater than 1016 pulses/s. The experimental time needed to collect this quite high number of records was prohibitive.

The recordings that were made included all modulation conditions for SAM pulse trains using the carrier rates of 504 and 1016 pulses/s. In addition, the recordings included all pulse rates for the unmodulated pulse trains. Stimuli were delivered to electrode 3, as in the psychophysical experiments, and recordings were made using the adjacent electrode 4 with reference to an electrode

Table 8. Maximum EP magnitudes recorded for each subject, for the conditions of Figs. 23-34.

Subject	Max EP magnitude	Stimulus condition
SR2	512 µV	300 Hz modulation of the 504 pulses/s carrier
SR3	260 µV	100 pulses/s, unmodulated pulse trains
SR9	54 µV	100 pulses/s, unmodulated pulse trains
SR10	159 µV	100 pulses/s, unmodulated pulse trains

at the ipsilateral mastoid. Additional details of the procedures used for recording intracochlear evoked potentials are presented in QPR 7.

Magnitudes of the evoked potentials following each stimulus pulse are presented for each of these various conditions in Figs. 23-25 for SR2, Figs. 26-28 for SR3, Figs. 29-31 for SR9, and Figs. 32-34 for SR10. The magnitudes in the plots are normalized to the maximum EP magnitude recorded among these conditions for each of the subjects. The maximum magnitudes recorded for each subject are presented in Table 8. Note that relatively large EPs are observed for SR2, whereas relatively small EPs are observed for SR9. The first 100 ms of the 200 ms records are presented in Figs. 23-34 to allow visualization of details in the temporal patterns of neural responses.

One aspect of the patterns might influence perception is the interval or intervals between principal peaks in the neural response (see, e.g., Cariani and Delgutte, 1996; Meddis and O'Mard, 1997). As an aid in identifying such intervals, we calculated the autocorrelation functions of the neural response patterns for each of the conditions in Figs. 23-34. Each function was calculated over the entire 200 ms of the responses, with a sufficient number of lags to show the function out to 12 ms. The neural response data were not windowed prior to calculation of the correlation for each lag. The results are presented in the right columns of Figs. 23-34, beside each of the respective plots of normalized EP magnitudes. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response.

Comparison of the plots of EP magnitudes in Fig. 23 with the patterns of stimulation in the left column of plots in Fig. 1 shows a similarity between stimuli and responses for the relatively low carrier rate of 504 pulses/s, at least for subject SR2. There is some evidence of relatively small refractory effects in the neural response data, e.g., the neural response to the second and sequential high amplitude pulse for the 100, 400 and 600 Hz modulation conditions is depressed compared to the response to the first pulse. Also, a minimum pulse amplitude is required to elicit a recordable EP. This is most obvious in the comparison of stimuli and responses for the 500 Hz modulation condition. Here, the neural responses "lag" the stimuli, in that neural responses rise above zero at approximately 50 ms into the record, whereas the pulse amplitudes begin increasing at the beginning of the record. This effect also may be seen for the remaining modulation conditions, i.e., no EPs are recorded for pulse amplitudes below a certain level.

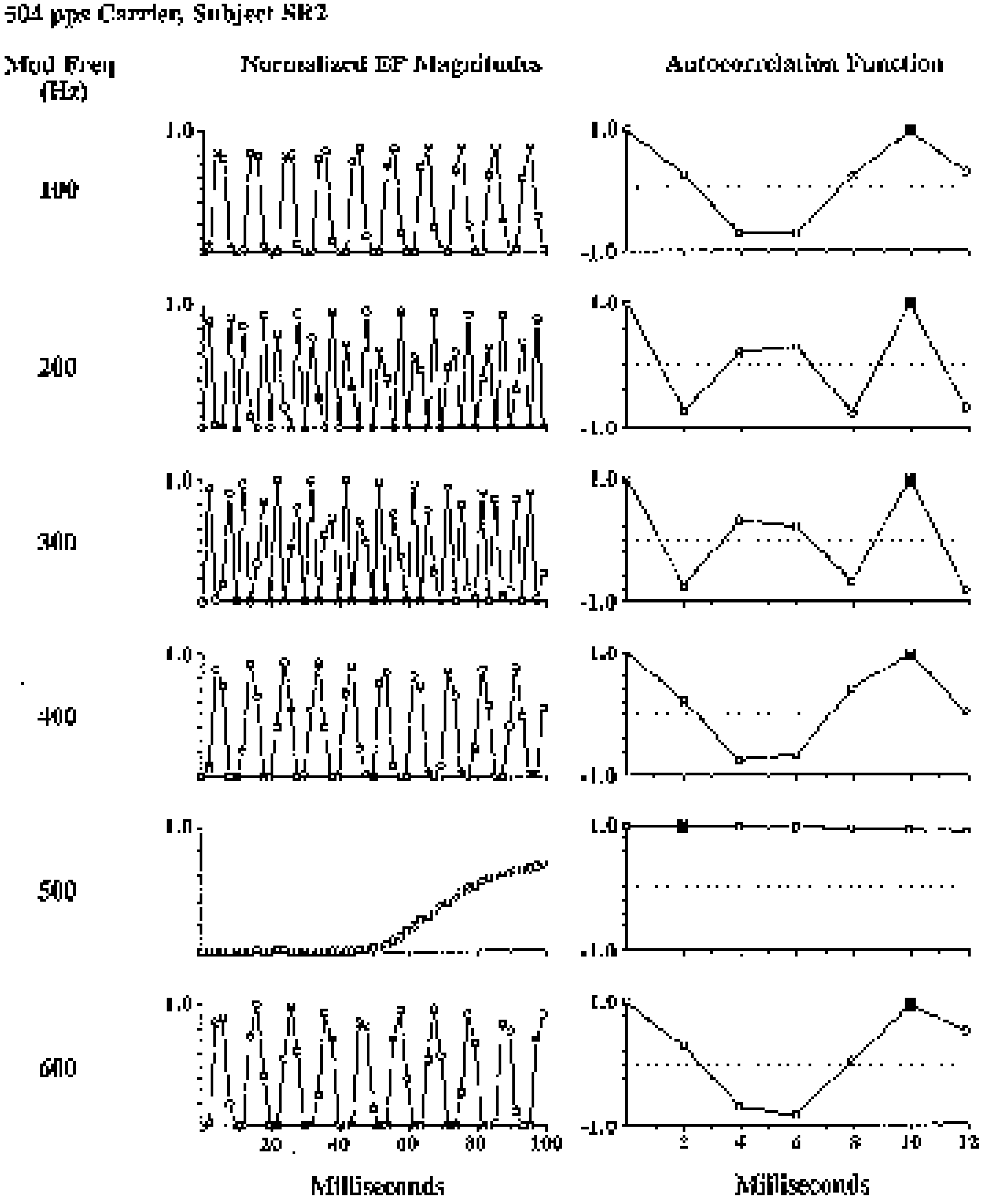


Fig. 23. Normalized EP magnitudes (middle column) and autocorrelation functions (right column) for auditory nerve responses to SAM pulse trains with the carrier rate of 504 pulses/s, subject SR2. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response. Modulation frequencies for the stimuli are shown in the left column. The carrier levels for each of the conditions are presented in Table 1.

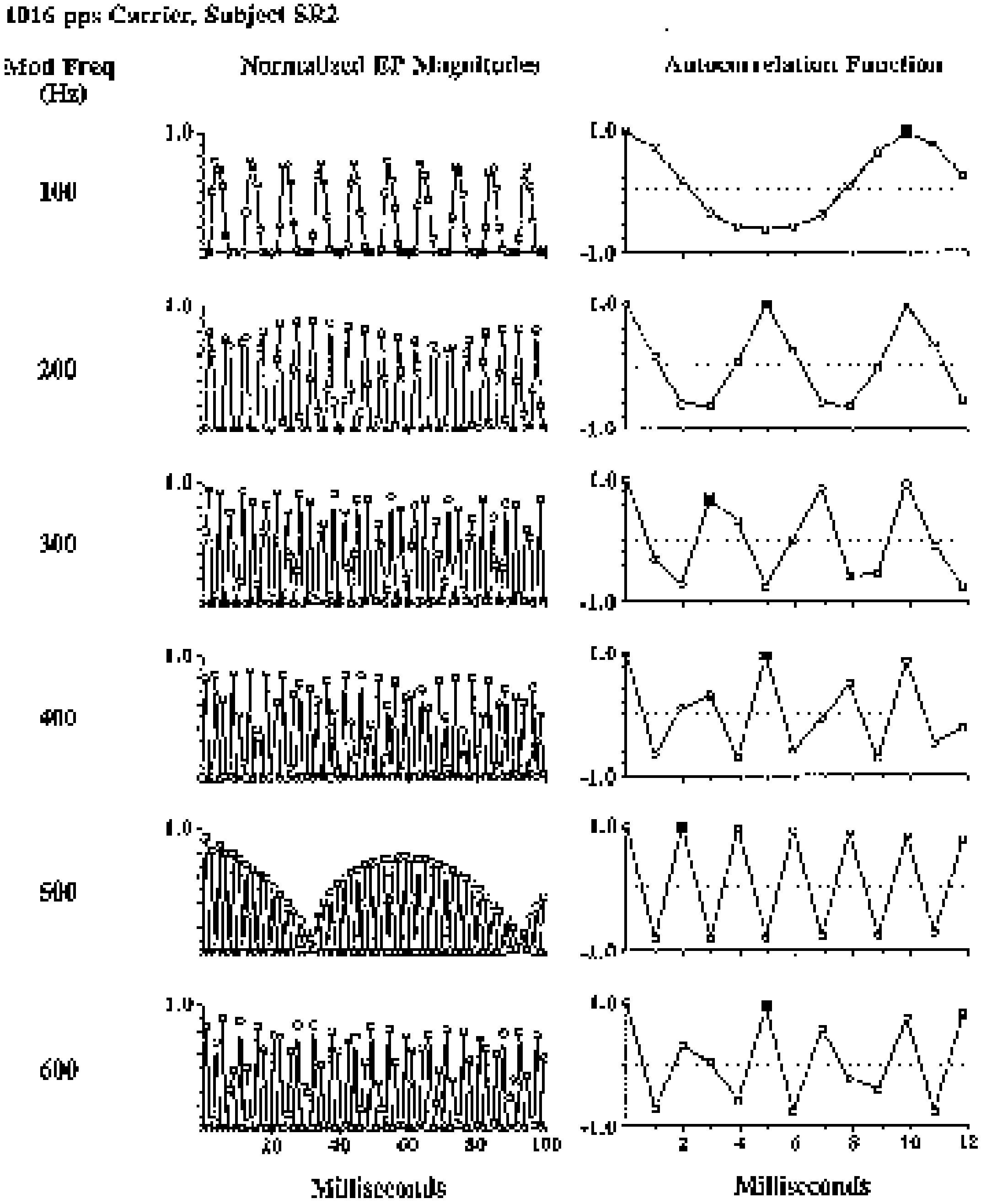


Fig. 24. Normalized EP magnitudes (middle column) and autocorrelation functions (right column) for auditory nerve responses to SAM pulse trains with the carrier rate of 1016 pulses/s, subject SR2. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response. Modulation frequencies for the stimuli are shown in the left column. The carrier levels for each of the conditions are presented in Table 1.

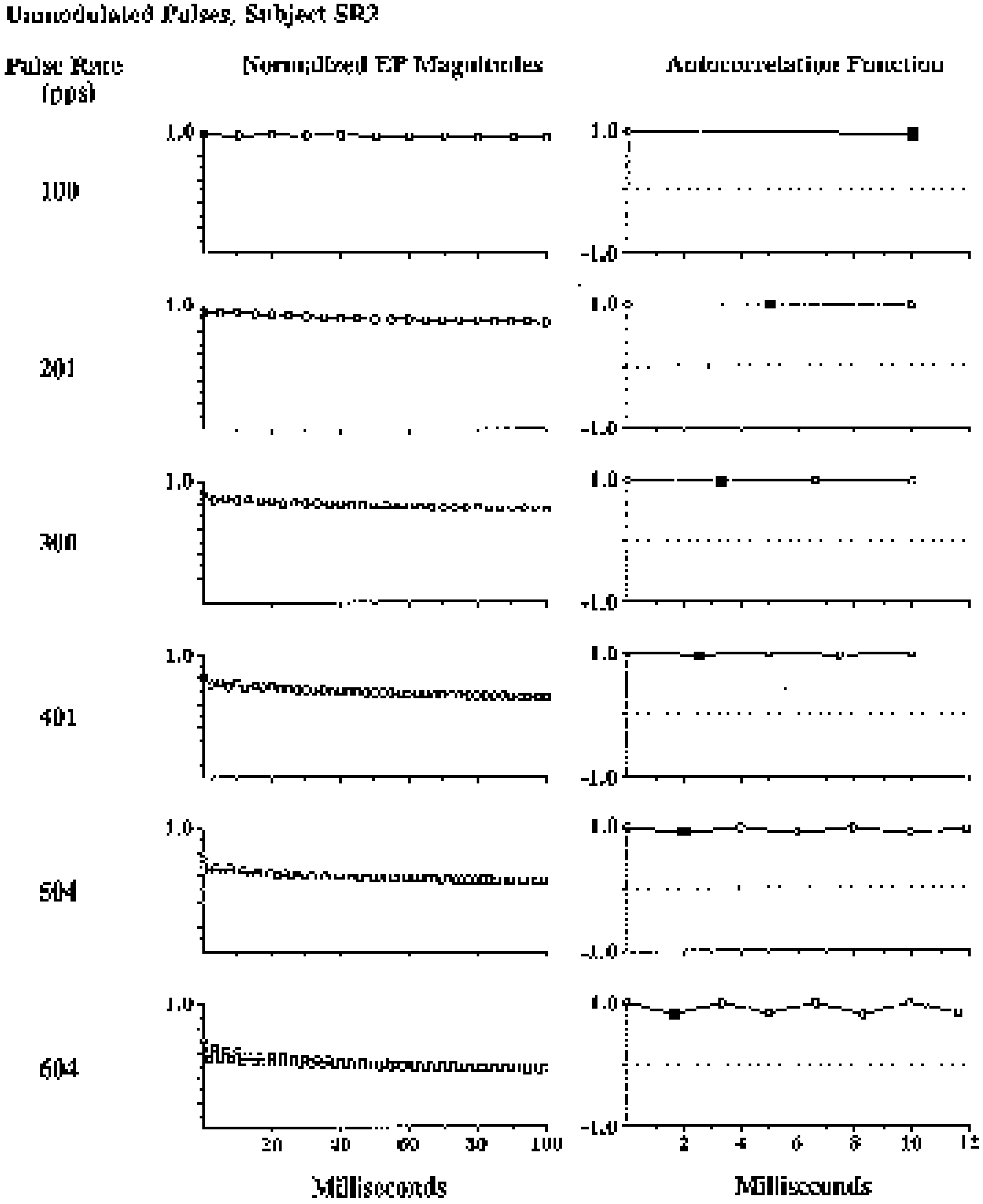


Fig. 25. Normalized EP magnitudes (middle column) and autocorrelation functions (right column) for auditory nerve responses to unmodulated pulse trains, subject SR2. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response. Pulse rates for the stimuli are shown in the left column. The pulse amplitudes for each of the conditions are presented in Table 1.

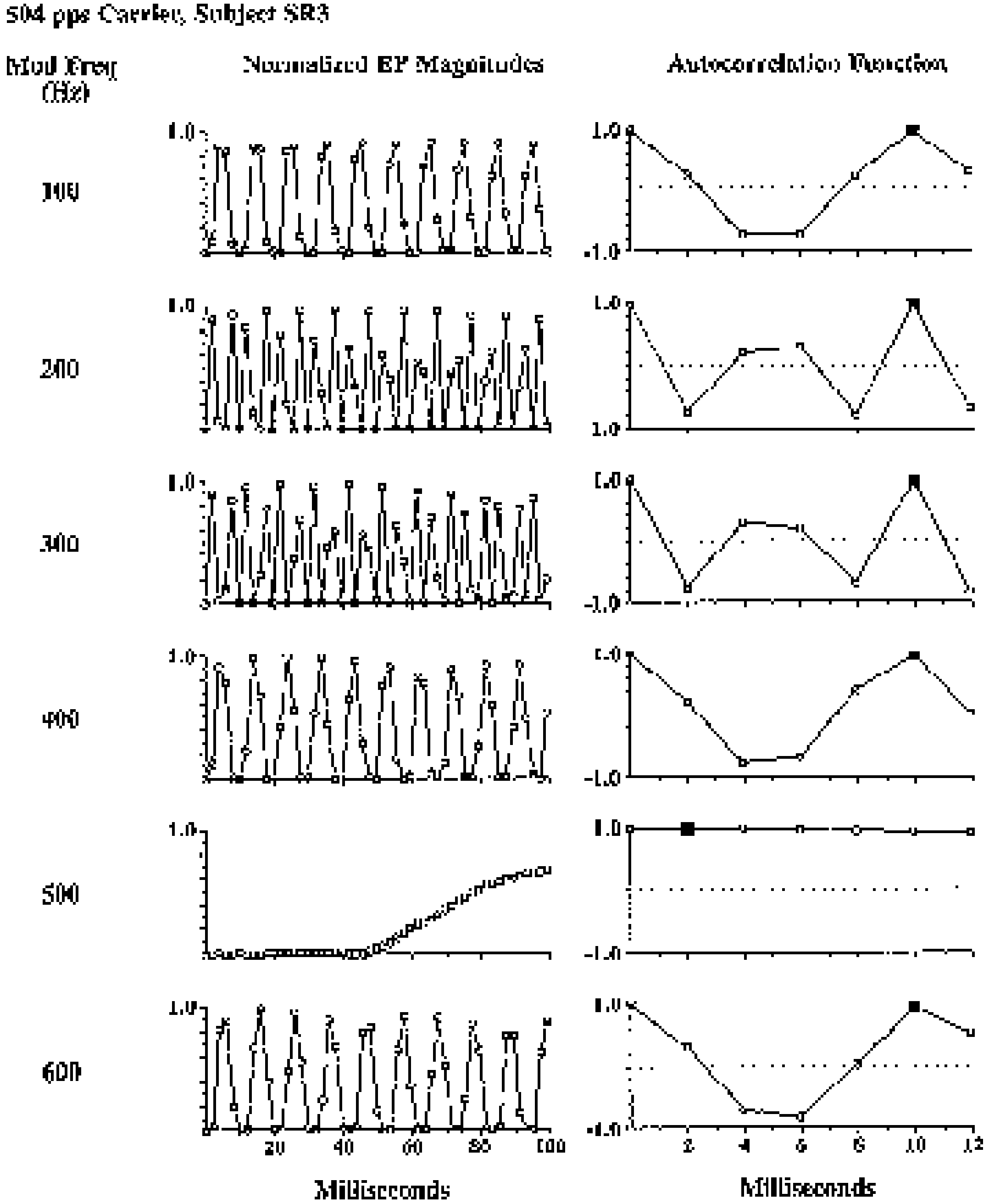


Fig. 26. Normalized EP magnitudes (middle column) and autocorrelation functions (right column) for auditory nerve responses to SAM pulse trains with the carrier rate of 504 pulses/s, subject SR3. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response. Modulation frequencies for the stimuli are shown in the left column. The carrier levels for each of the conditions are presented in Table 1.

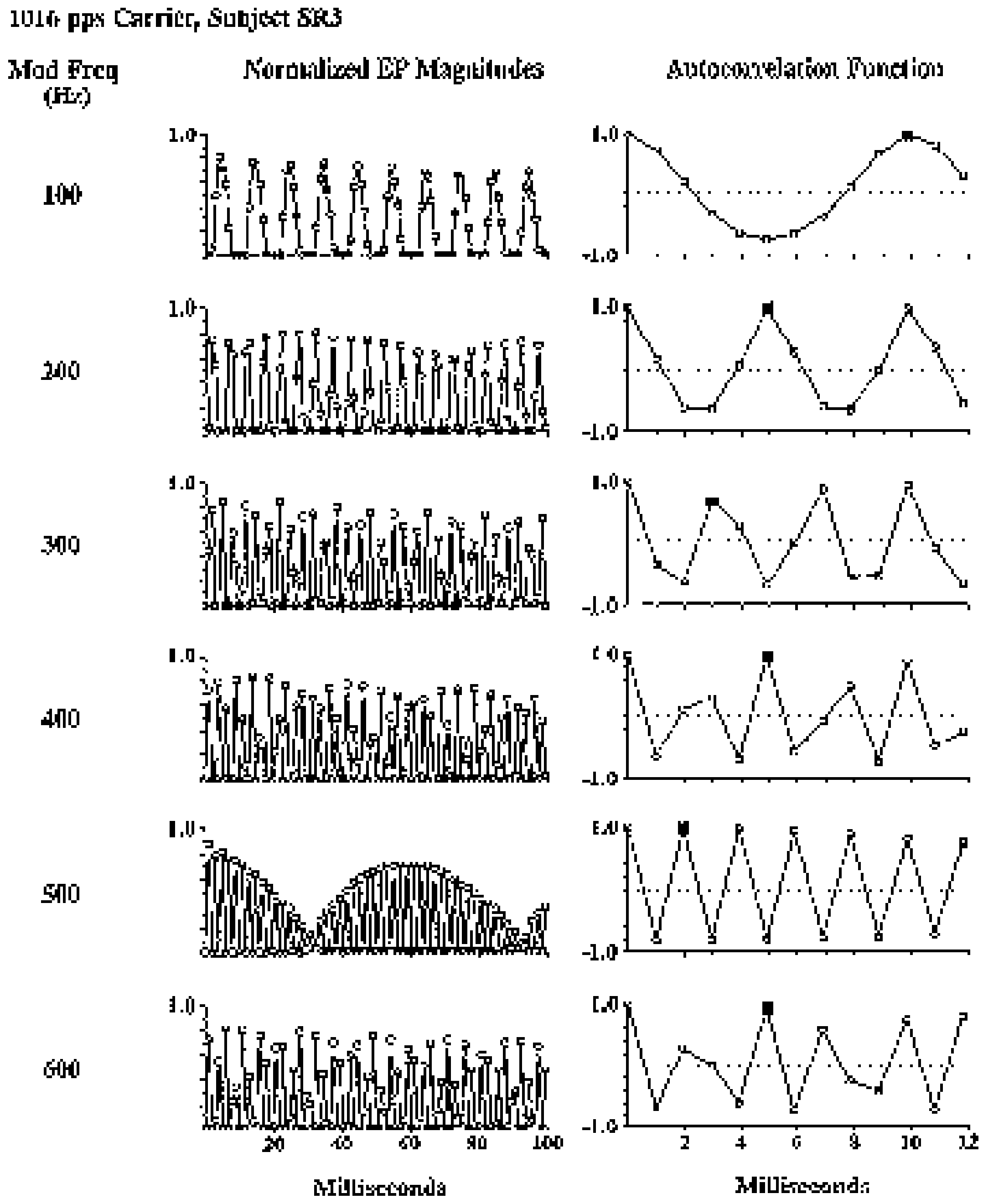


Fig. 27. Normalized EP magnitudes (middle column) and autocorrelation functions (right column) for auditory nerve responses to SAM pulse trains with the carrier rate of 1016 pulses/s, subject SR3. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response. Modulation frequencies for the stimuli are shown in the left column. The carrier levels for each of the conditions are presented in Table 1.

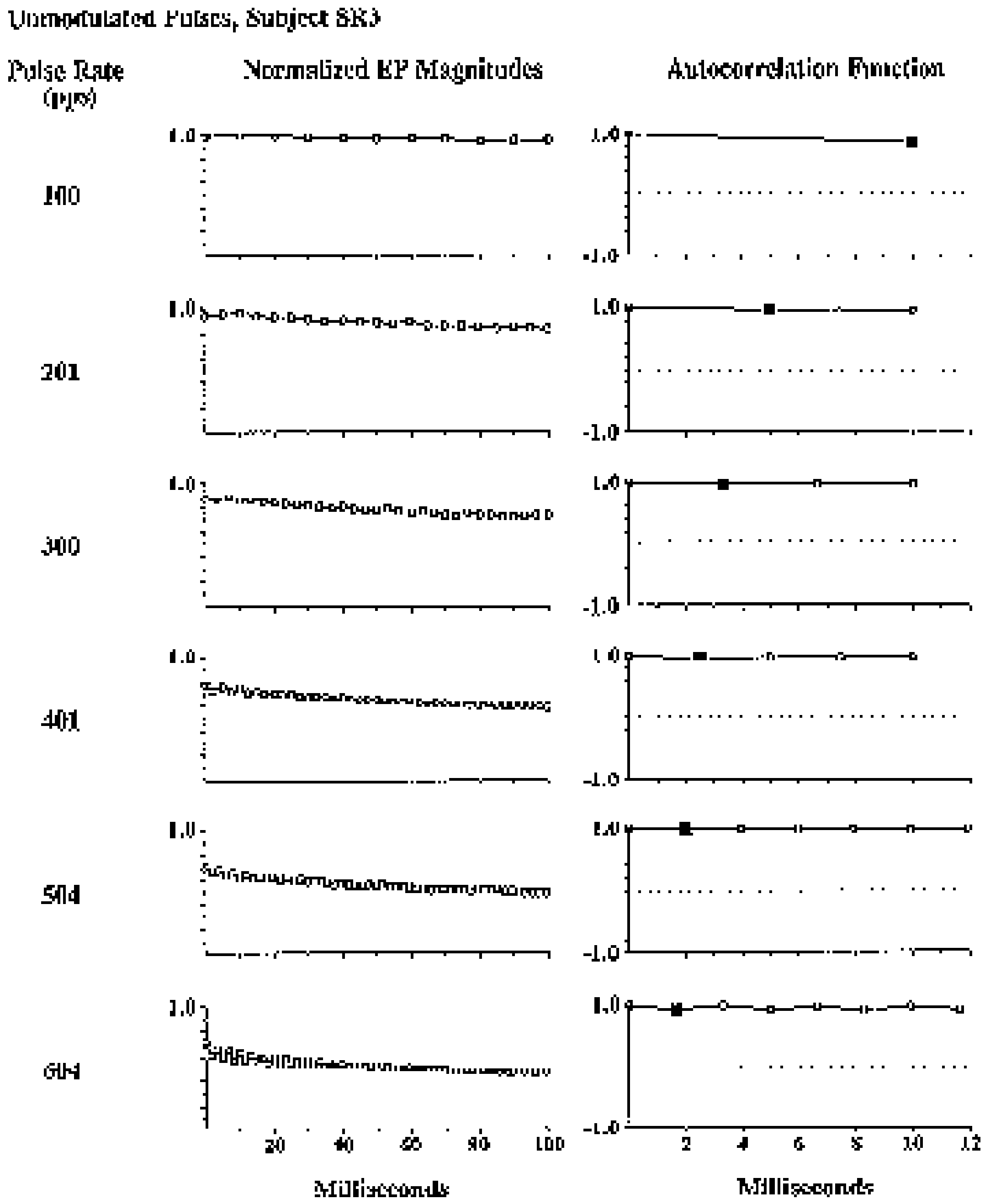


Fig. 28. Normalized EP magnitudes (middle column) and autocorrelation functions (right column) for auditory nerve responses to unmodulated pulse trains, subject SR3. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response. Pulse rates for the stimuli are shown in the left column. The pulse amplitudes for each of the conditions are presented in Table 1.

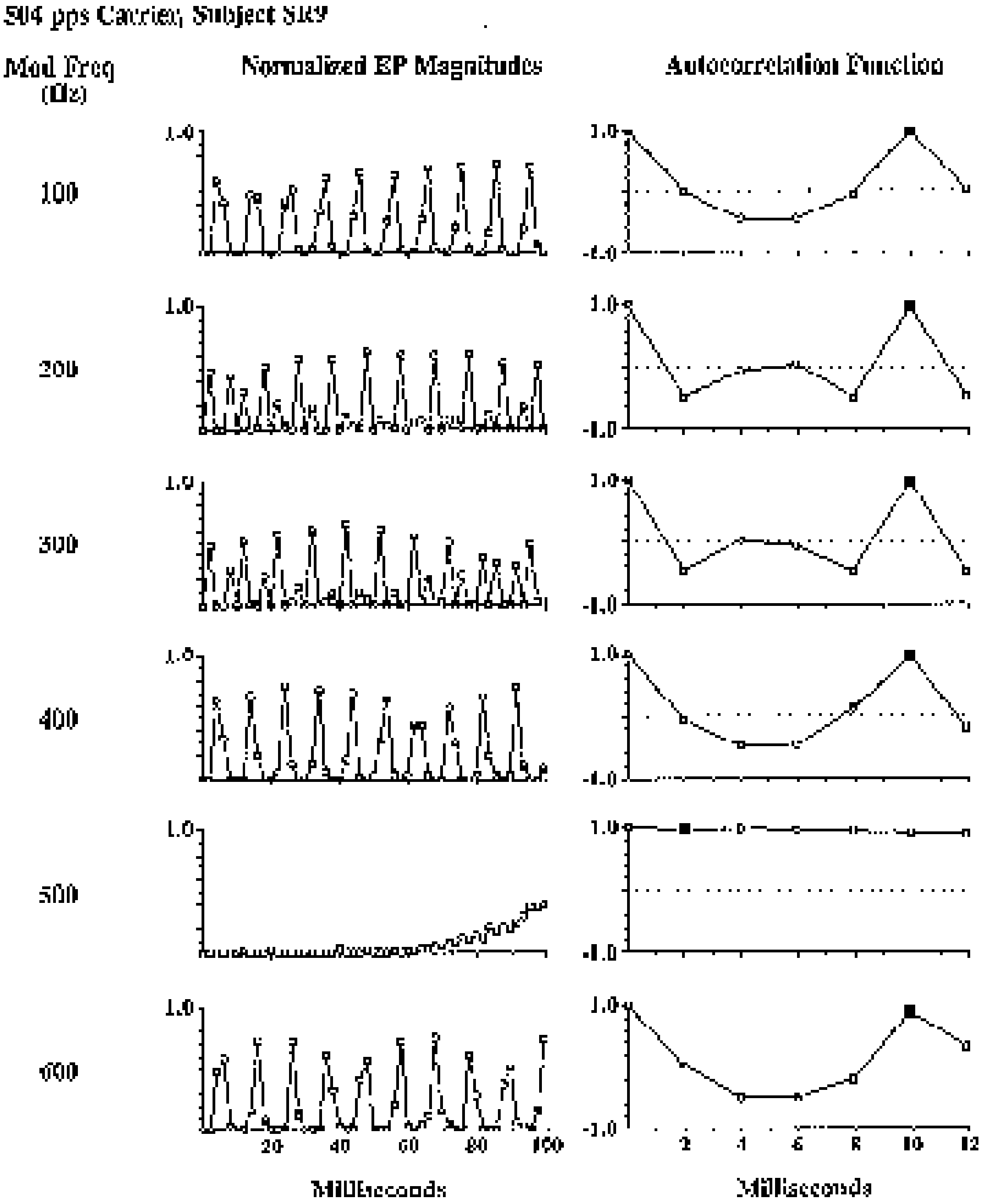


Fig. 29. Normalized EP magnitudes (middle column) and autocorrelation functions (right column) for auditory nerve responses to SAM pulse trains with the carrier rate of 504 pulses/s, subject SR9. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response. Modulation frequencies for the stimuli are shown in the left column. The carrier levels for each of the conditions are presented in Table 1.

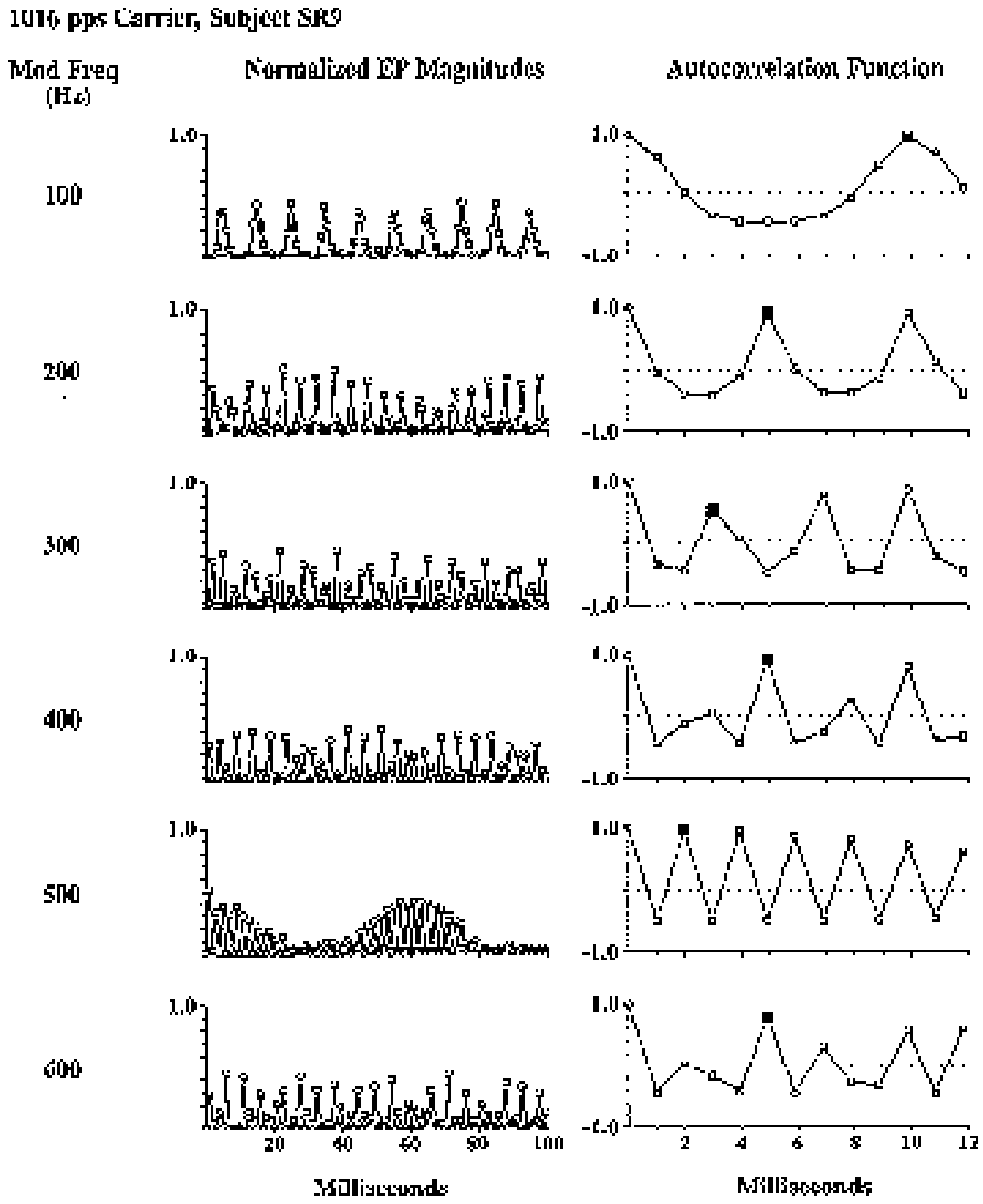


Fig. 30. Normalized EP magnitudes (middle column) and autocorrelation functions (right column) for auditory nerve responses to SAM pulse trains with the carrier rate of 1016 pulses/s, subject SR9. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response. Modulation frequencies for the stimuli are shown in the left column. The carrier levels for each of the conditions are presented in Table 1.

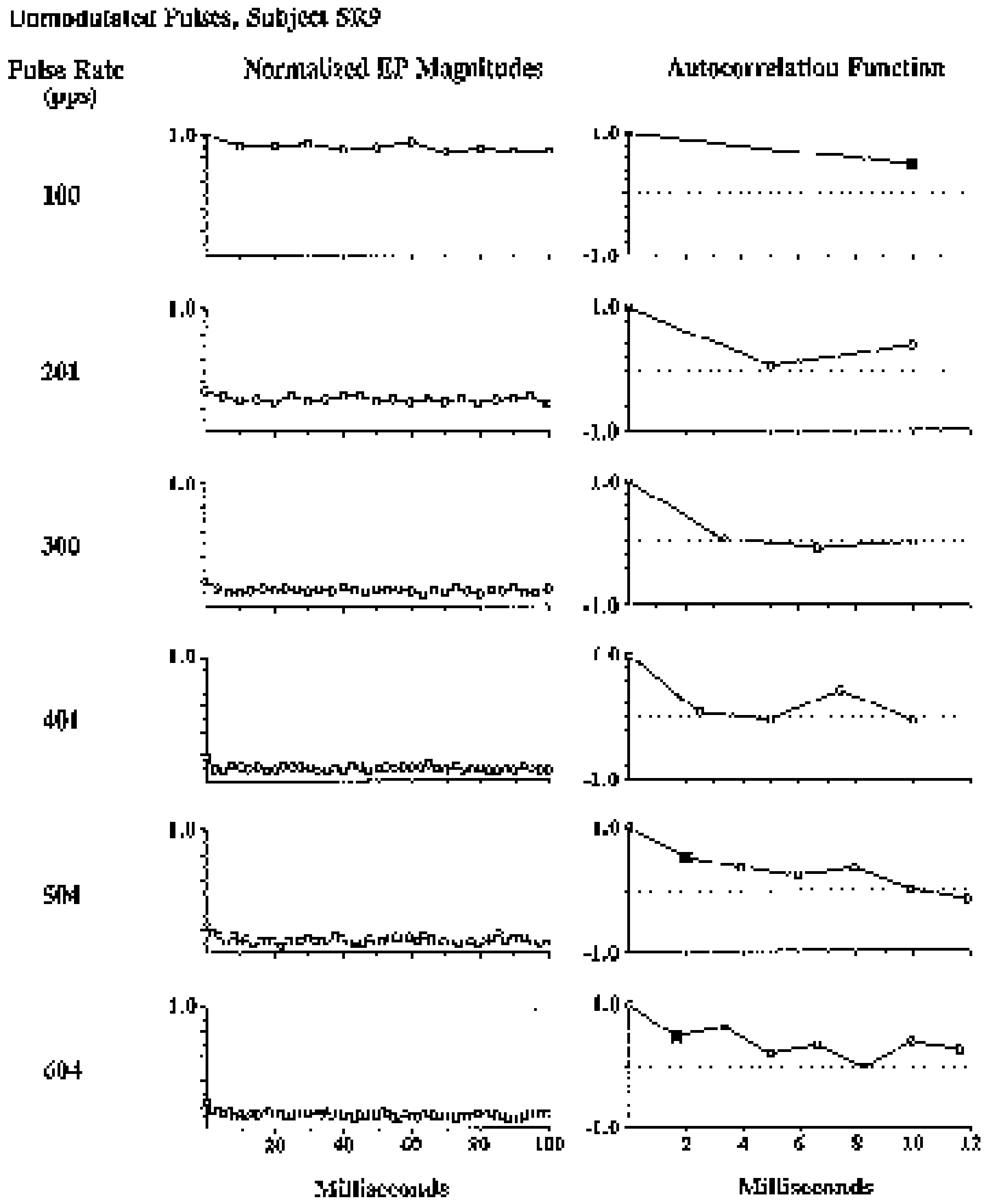


Fig. 31. Normalized EP magnitudes (middle column) and autocorrelation functions (right column) for auditory nerve responses to unmodulated pulse trains, subject SR9. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response. Pulse rates for the stimuli are shown in the left column. The pulse amplitudes for each of the conditions are presented in Table 1.

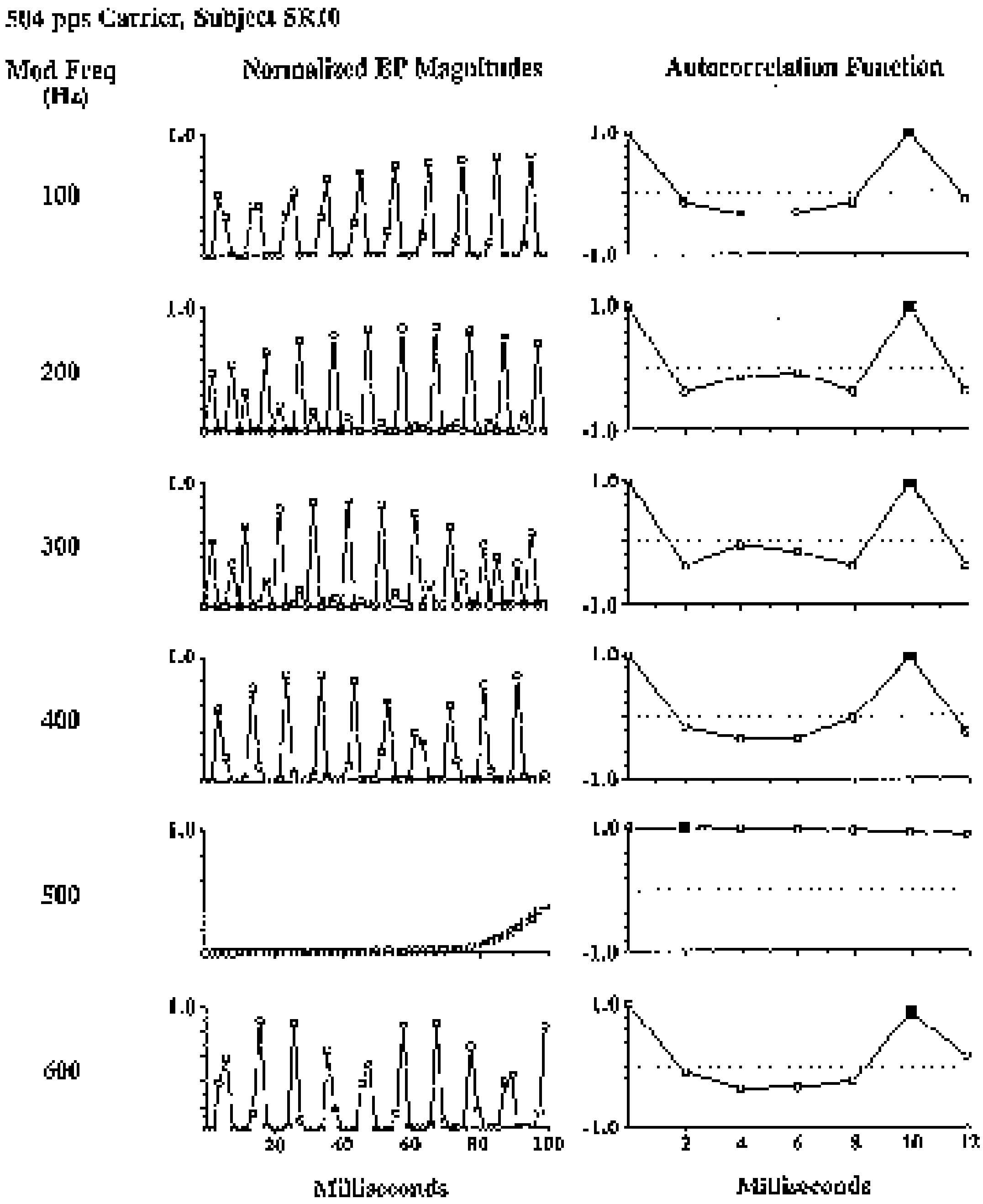


Fig. 32. Normalized EP magnitudes (middle column) and autocorrelation functions (right column) for auditory nerve responses to SAM pulse trains with the carrier rate of 504 pulses/s, subject SR10. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response. Modulation frequencies for the stimuli are shown in the left column. The carrier levels for each of the conditions are presented in Table 1.

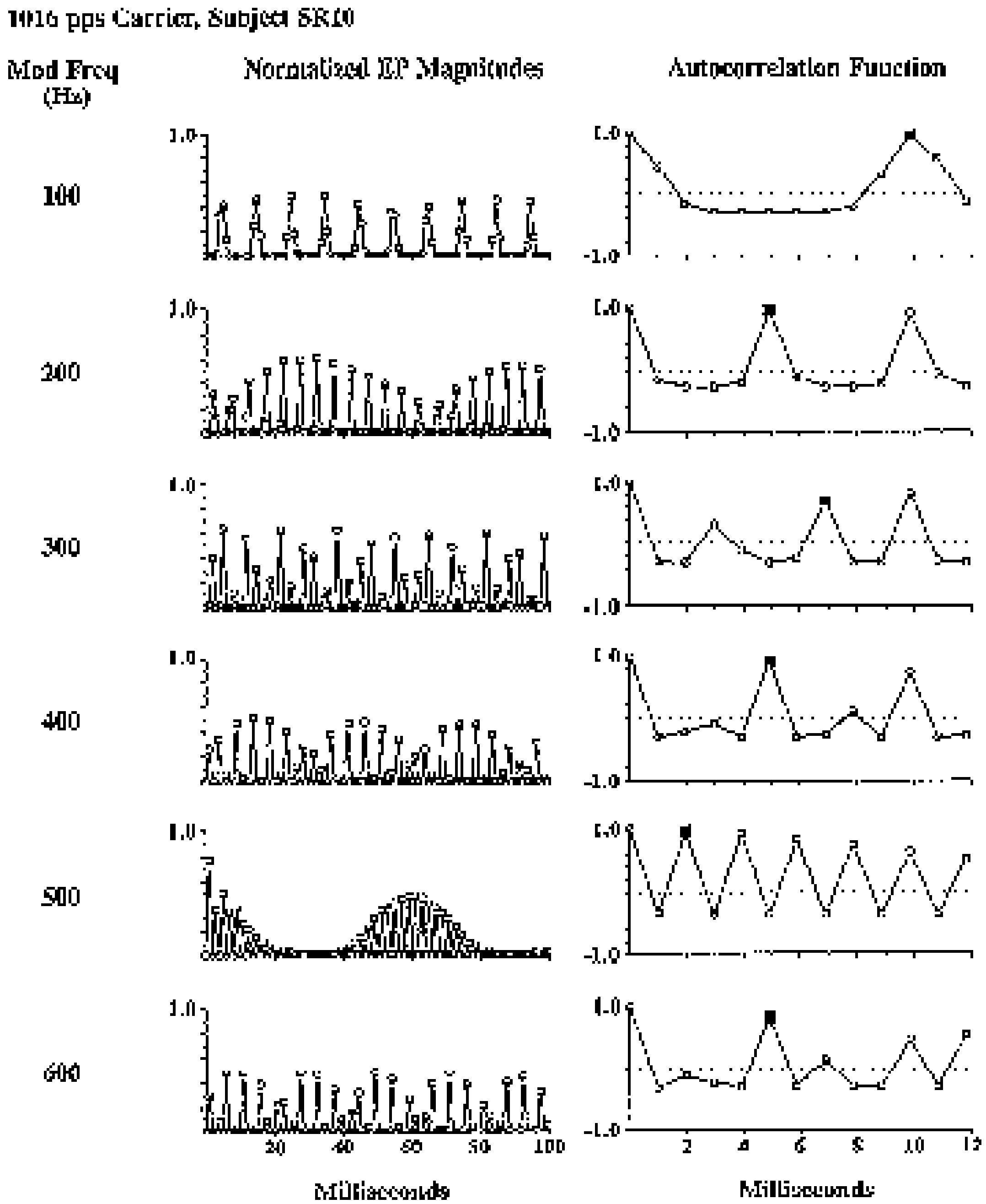


Fig. 33. Normalized EP magnitudes (middle column) and autocorrelation functions (right column) for auditory nerve responses to SAM pulse trains with the carrier rate of 1016 pulses/s, subject SR10. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response. Modulation frequencies for the stimuli are shown in the left column. The carrier levels for each of the conditions are presented in Table 1.

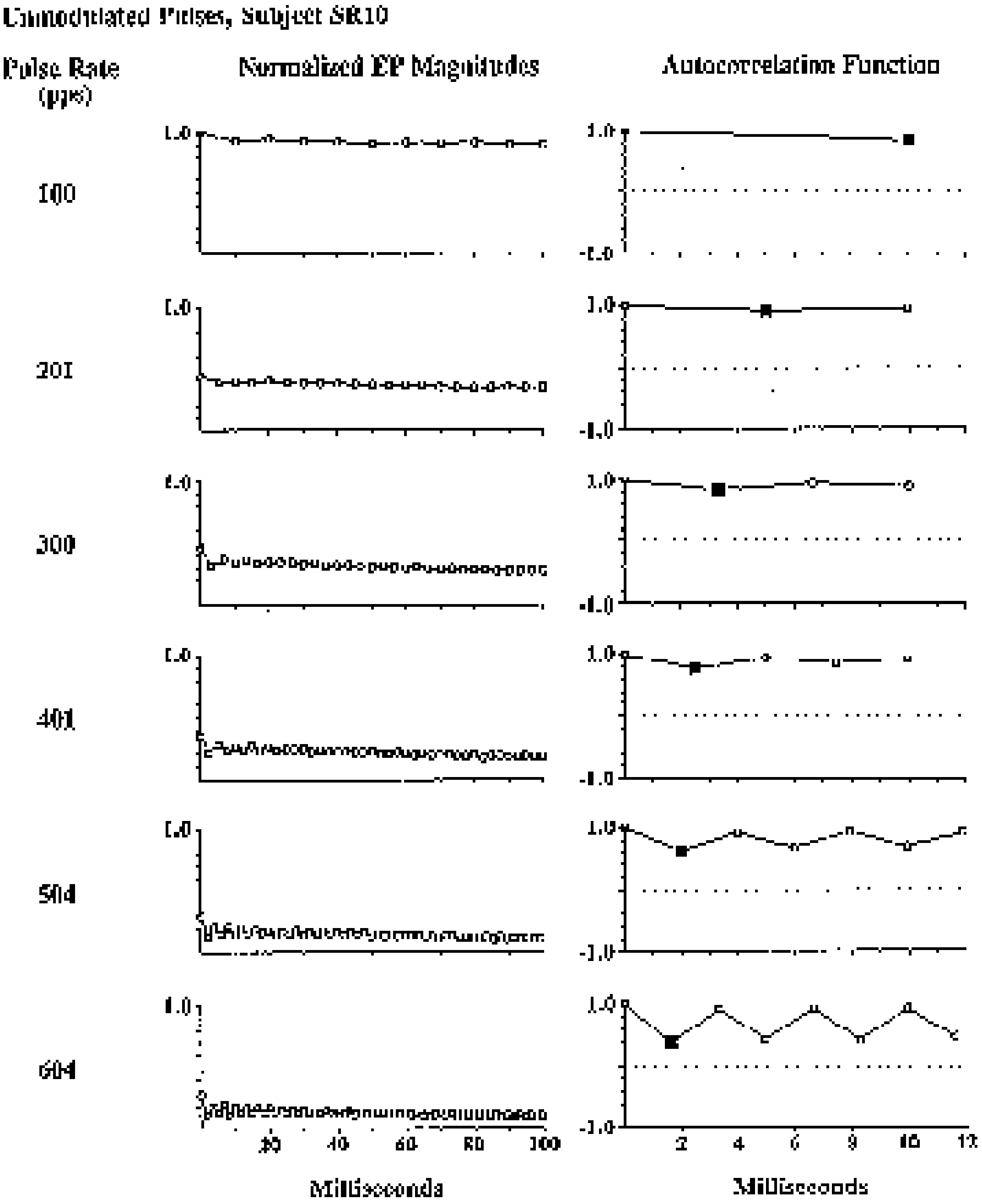


Fig. 34. Normalized EP magnitudes (middle column) and autocorrelation functions (right column) for auditory nerve responses to unmodulated pulse trains, subject SR10. Filled symbols in the plots of the autocorrelation functions indicate prominent peaks in the functions, corresponding to prominent intervals in the patterns of neural response. Pulse rates for the stimuli are shown in the left column. The pulse amplitudes for each of the conditions are presented in Table 1.

The principal interval in the pattern of neural responses for the 100 Hz modulation condition is 10 ms, as may be identified in this case by inspection of the record. The autocorrelation function shows this as well, with a peak at 10 ms.

Multiple intervals are observed for the 200 and 300 Hz modulation conditions, as shown by both the neural response records and corresponding autocorrelation functions. The principal interval between the highest peaks in the neural response patterns for both modulation conditions is 10 ms, as indicated by inspection of the records and by the large peaks in the autocorrelation functions at 10 ms. The autocorrelation function for the 200 Hz modulation condition also shows significant peaks at 4 and 8 ms, and the autocorrelation function for the 300 Hz modulation condition also shows a significant peak at 4 ms. These intervals can be seen in the corresponding neural response plots. For example, in the plot for the 200 Hz modulation condition, the peaks at the 5th and 7th points, and at the 10th and 12th points, are separated by 4 ms.

Only one interval is observed between principal peaks for the 400 and 600 Hz modulation conditions, 10 ms. The patterns of neural responses for the conditions are similar to the pattern observed for the 100 Hz modulation condition.

Responses for the 500 Hz modulation condition are relatively uniform in magnitude over intervals of 12 ms or less. Thus, the principal interval between successive “peaks” in the response is 2 ms, as identified in the autocorrelation function. In this case, the “peaks” are not separated by valleys. The autocorrelation function also shows high values for successive lags beyond 2 ms, which is to be expected inasmuch as shifting the neural response pattern by additional 2 ms steps still will produce close replicates of the unshifted record.

Comparison of the stimuli and neural responses (for SR2) for the SAM pulse trains with the carrier rate of 1016 pulses/s (right column of Fig. 1 compared with the left column of Fig. 24) also shows a correspondence between stimuli and responses. However, the correspondence is not as strong as that observed for the 504 pulses/s carrier conditions, as the effects of refraction are greater with the higher carrier rate. In general, the neural responses for the 1016 pulses/s carrier are more “peaked” than the stimuli, as a result of such effects. Also, as with the 504 pulses/s carrier conditions, neural responses are not recorded for pulse amplitudes below a certain level. One obvious manifestation of this is in the record for the 500 Hz modulation condition. The neural response in this case looks like a half-wave rectified version of the stimulus.

Single intervals are observed between the principal peaks in the responses for the 100, 200 and 500 Hz modulation conditions. The autocorrelation functions for the 200 and 500 Hz modulation conditions show a large peak corresponding to the intervals for these conditions and also show additional large peaks at multiples of the interval, which fall within the 12 ms over which the present autocorrelation functions are calculated.

Multiple intervals are observed for the remaining modulation conditions. The first peak with a high correlation is identified for each condition, and that peak corresponds to one of the intervals. Other intervals present in the auditory nerve responses might affect perception. These additional intervals for the 300 Hz modulation condition include 7 and 10 ms, for the 400 Hz modulation condition 3 and 8 ms, and for the 600 Hz modulation condition 2, 7 and 10 ms.

Patterns of response for the unmodulated pulse trains reflect the uniform amplitudes of the stimulus pulses over the present range of pulse rates and for subject SR2 (Fig. 25). EP magnitudes are highly uniform up to and including the pulse rate of 400 pulses/s. A shallow alternation in EP magnitudes for sequential pulses is observed in the initial parts of the records for the 500 and 600 pulses/s conditions, as has been previously described (e.g., in QPR 7). This alternation most likely reflects the onset of refractory effects.

Not surprisingly, the autocorrelation functions for these response patterns also are relatively simple. Each function shows a high correlation at the interval separating the approximately uniform neural responses for sequential stimulus pulses. The functions for the 200 pulses/s and higher conditions also show high correlations at multiples of the base interval. The functions for the 500 and 600 pulses/s conditions show an alternation, corresponding to the alternation of EP magnitudes in the neural response records.

The results for subject SR3 (Figs. 26-28) are almost identical to those described above for SR2. The only notable (but still small) difference is in the patterns of results for the 500 and 600 pulses/s conditions using the unmodulated pulse trains. The results for SR3 show a somewhat shallower alternation in EP magnitudes from pulse to pulse than the results for SR2 (compare Figs. 25 and 28). Indeed, the results for SR3 do not show any obvious alternation for the 500 pulses/s condition. Similarly, the autocorrelation functions for SR3 do not show any alternation for the 500 pulses/s condition and only a slight alternation (compared with SR2) for the 600 pulses/s condition.

Results for SR9 (Figs. 29-31) and SR10 (Figs. 32-34) are different in some respects from those for SR2 and SR3. For the SAM pulse trains using the 504 pulses/s carrier, results for SR9 and SR10 show relatively simple patterns of response for the 200 and 300 Hz modulation conditions. For them, only one interval separates principal peaks in the responses for each of these conditions. Unlike SR2 and SR3, only the correlation at 10 ms is significant. The “secondary” intervals identified in the autocorrelation functions for SR2 and SR3, at 4 and 6 ms for these conditions, are not indicated in the autocorrelation functions for SR9 and SR10 (i.e., the correlation values at these lags are not significant). The simpler patterns of responses for SR9 and SR10 probably reflect relatively high thresholds for eliciting a recordable EP. Such thresholds are indicated, for example, by the relatively late onset of increasing EP magnitudes for these subjects for the 500 Hz modulation condition. EPs begin to rise above zero at 50 ms for subjects SR2 and SR3, whereas EPs begin to rise above zero at about 75 to 80 ms for subjects SR9 and SR10. The high thresholds for SR9 and SR10 eliminate the complexities observed in the responses for SR2 and SR3, which include responses to pulses with relatively low amplitudes.

In addition the differences just noted, responses for the 600 Hz modulation condition suggest the presence of a low frequency component for SR9 and SR10, beyond the 12 ms limit of the autocorrelation calculations. This may be seen in the highest peaks for these records, where pairs of high peaks (pair 1 at about 16 and 26 ms, and pair 2 at about 58 and 68 ms) are separated by about 42 ms. (This is somewhat more evident in the record for SR10, Fig. 32, lower left panel.)

Relatively simple patterns of response also are observed for SR9 and SR10 when the carrier rate is increased to 1016 pulses/s (Figs. 30 and 33, respectively). The differences between these records and those for SR2 and SR3 are most pronounced for the 300, 400 and 600 Hz modulation conditions. For the 300 Hz condition, the high correlation observed at 3 ms observed for SR2 and SR3 is diminished in the autocorrelation functions for SR9 and SR10. Also, the correlation at 7 ms is relatively high in the functions for SR9 and SR10. Indeed, the principal interval identified in the autocorrelation function for SR10 is 7 ms, as opposed to the 3 ms interval identified for the remaining subjects.

For the 400 Hz modulation conditions, the correlations at 3 ms are highly significant for SR2 and SR3, whereas these correlations are not significant for SR9 and SR10. In addition, the correlation at 8 ms is not significant for SR10 and is much diminished (but still significant) for SR9.

The correlations at 2 ms for the 600 Hz modulation condition are significant for subjects SR2 and SR3, but not significant for SR9 and SR10. In addition, the correlations at 7 ms are lower for subjects

SR9 and SR10 compared with SR2 and SR3. Indeed, the correlation is not significant for subject SR10.

As with the 504 pulses/s carrier, the neural response records for SR9 and SR10 suggest the possibility of low frequency components for some of the modulation conditions used with the 1016 pulses/s carrier. A pattern of responses is repeated at about 30 ms intervals in the 400 Hz modulation records for both subjects. In addition, a different pattern is repeated at about 22 ms intervals in the 600 Hz modulation record for SR10. The presence of such low frequency components may influence perception.

Responses to trains of unmodulated pulses for SR9 and SR10 are also different from those of SR2 and SR3. Relatively high levels of response are maintained across pulse rates for SR2 and SR3 (for the pulse amplitudes that produce equal loudnesses among these pulse rate conditions), whereas magnitudes of response for SR9 and SR10 are markedly reduced with increases in pulse rate above 100 pulses/s. For SR9, the reduction in response magnitude, along with the relatively low signal-to-noise ratios of recordings for her, diminished the power of the autocorrelation function to identify intervals between principal events in the response. Indeed, the correlations for the interval between sequential pulses, and between roughly uniform EPs corresponding to those pulses, are not significant for the 201, 300 and 401 pulses/s conditions for SR9. Also, the alternating pattern of response observed for SR2, SR3 and SR10 at 600 pulses/s is not apparent in the (relatively noisy) record for SR9.

The records for SR10 are less noisy, and the autocorrelation functions for him show significant correlations at the reciprocal of the pulse rate for all pulse rate conditions. SR10 also shows some alternation in the initial part of the neural response record for the 401 pulses/s condition, and relatively high levels of alternation in the 504 and 604 pulses/s conditions, compared with the records for subjects SR2 and SR3. These relatively high levels of alternation are reflected in the autocorrelation functions for SR10, which also show a strong alternating patterns for these conditions. The very high correlation at 3.3 ms for the 600 Hz condition identifies an interval that might affect perception, in addition to the "principal" interval of 1.65 ms.

Comparisons of psychophysical and electrophysiological measures

Comparisons of pitch judgments versus a measures derived from the principal interval or intervals in neural recordings using the same stimuli are presented in Figs. 35 through 40. The measure derived from the principal interval or intervals in the neural recordings is the logarithm of the reciprocal of the interval(s). The reciprocal provides a measure in Hz, and the logarithm transforms that measure into a ratiometric scale like that found in normal hearing for perception of pitch as the frequency of stimulation is changed.

Comparisons for the SAM pulse trains using the carrier rates of 504 and 1016 pulses/s, along with comparisons for the unmodulated pulse trains, are presented in Figs. 35, 36, 37 and 39 for subjects SR2, SR3, SR9 and SR10, respectively. These comparisons use the principal interval (i.e., the most

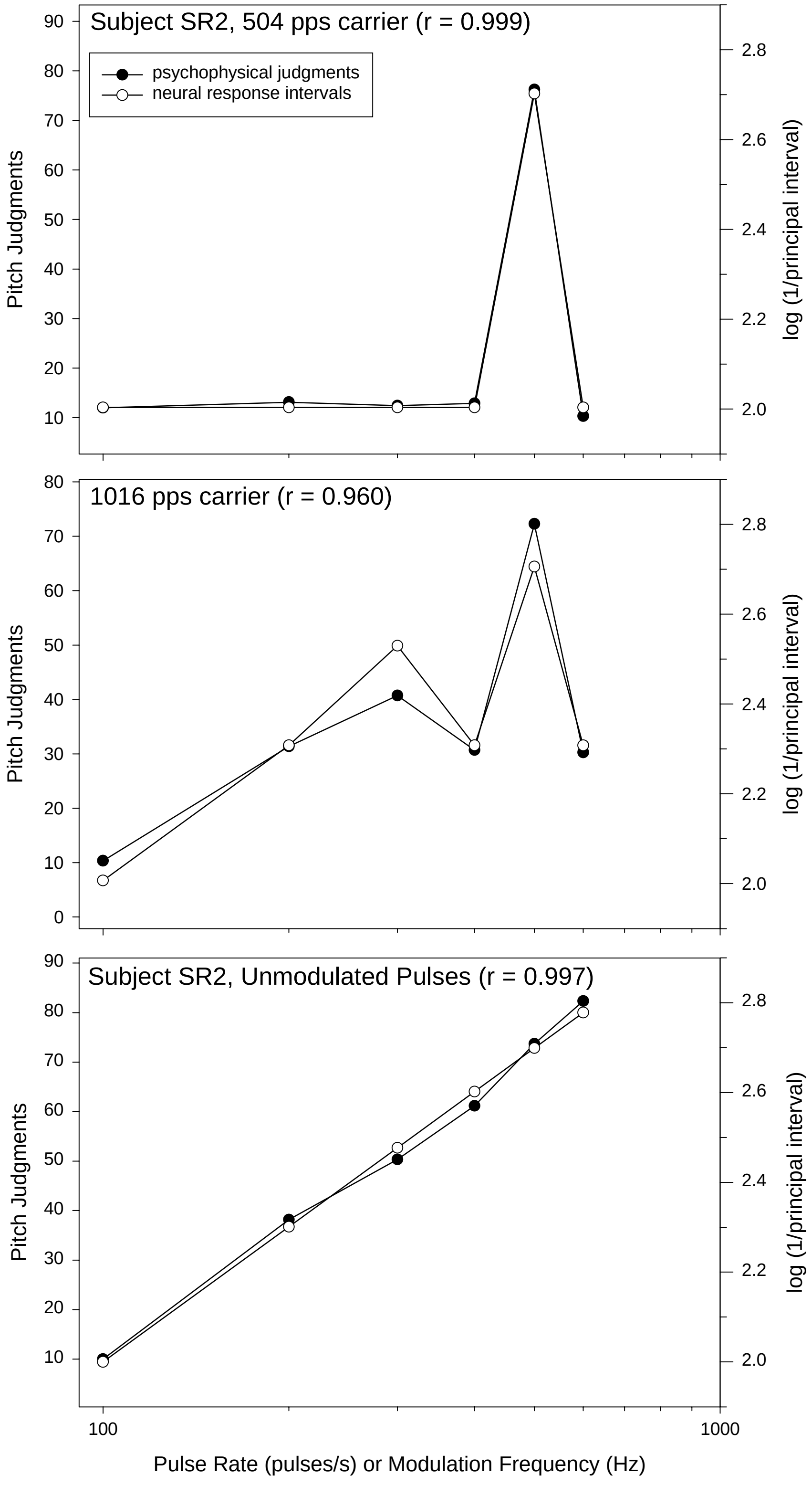


Fig. 35. Comparisons of psychophysical judgments versus intervals between principal peaks or events in the neural response patterns for the same stimuli, subject SR2.

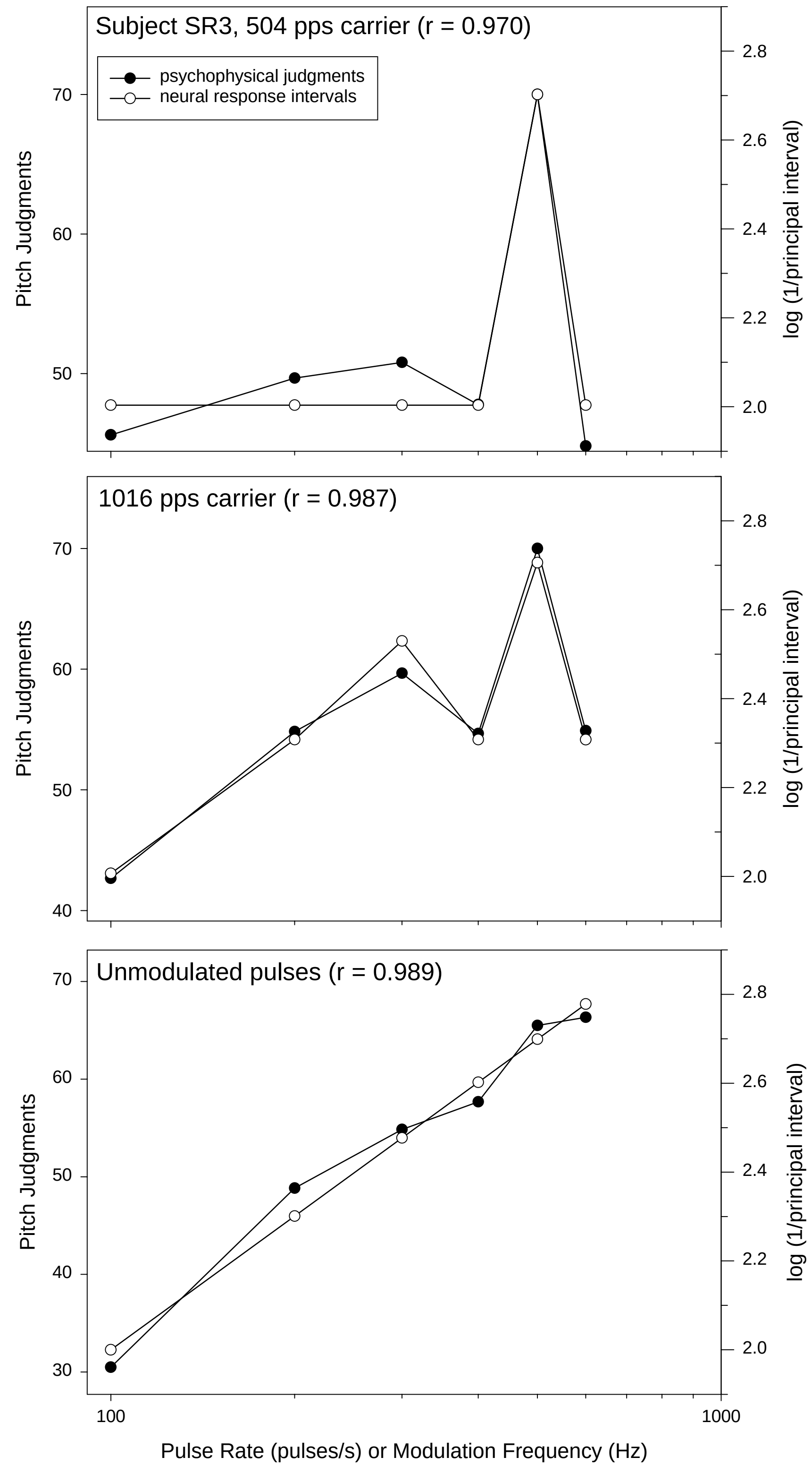


Fig. 36. Comparisons of psychophysical judgments versus intervals between principal peaks or events in the neural response patterns for the same stimuli, subject SR3.

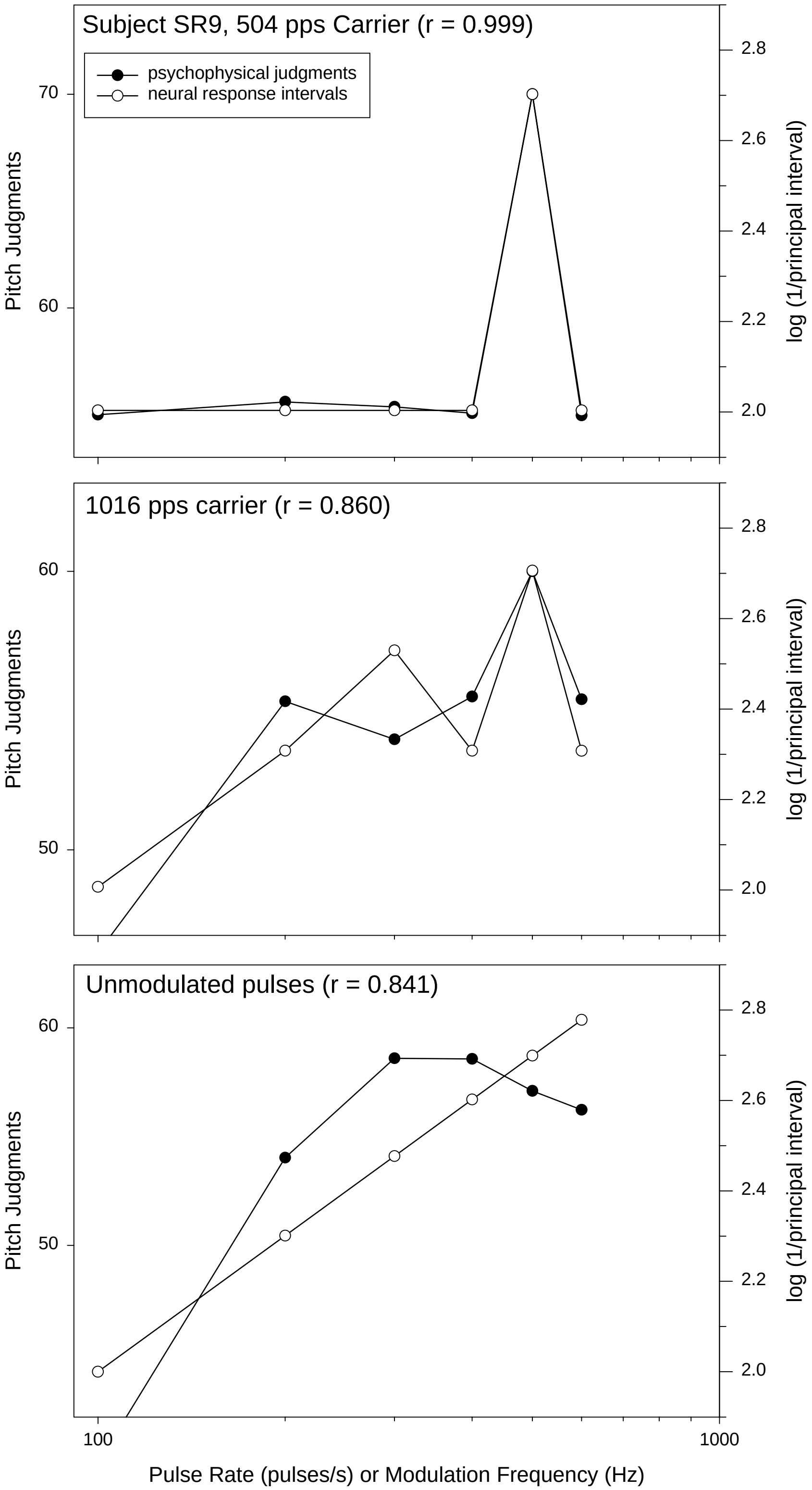


Fig. 37. Comparisons of psychophysical judgments versus intervals between principal peaks or events in the neural response patterns for the same stimuli, subject SR9.

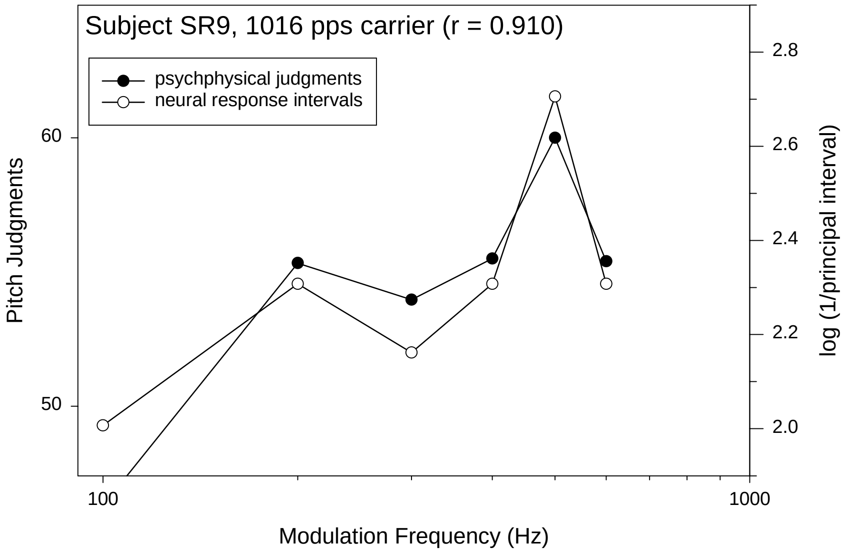


Fig. 38. Comparisons of psychophysical judgments versus intervals between principal peaks or events in the neural response patterns for the same stimuli, subject SR9, using an alternative set of intervals for the 1016 pulses/s carrier conditions.

prominent interval at a short autocorrelation lag) for each condition, as identified in Figs. 23-34. A additional comparison for SR9 is presented in Fig. 38, using an alternative set of intervals for the 1016 pulses/s carrier conditions. An additional comparison for SR10 is presented in Fig. 40, also using an alternative set of intervals for the 1016 pulses/s carrier conditions.

Results for SR2 (Fig. 35) show strong correlations between pitch judgments and the measure based on principal intervals in the neural response patterns. Each of these correlations is highly significant ($p < 0.001$ for 504 pulses/s carrier conditions and for the unmodulated pulse train conditions, and $p < 0.005$ for the 1016 pulses/s carrier conditions). The agreement between the perceptual and neural data is striking, especially for the 504 pulses/s carrier conditions ($r = 0.999$) and for the unmodulated pulse train conditions ($r = 0.997$). This suggests that intervals between principal peaks or events in the population response of the auditory nerve are utilized by the central nervous system in making judgments about pitch. The spectrum of the stimulus does not necessarily affect pitch. For example, the 200 Hz component in the SAM pulse train produced with 200 Hz modulation of the 504 pulses/s carrier apparently is not perceived, as the judgment for this stimulus is no different from the judgment for the 100 Hz modulation condition (with the same carrier).

The results for SR2 also suggest that intervals as short as 1.67 ms can be perceived by at least some implant patients. That is, there is no evidence in the bottom panel of Fig. 35 that the slope of pitch changes over the range of tested pulse rates up to and including 600 pulses/s.

The only departure from a nearly perfect fit among the comparisons presented in Fig. 35 is the difference between the pitch judgment and corresponding neural measure for 300 Hz modulation of the 1016 pulses/s carrier (middle panel). This difference may have been produced by the presence of multiple intervals in the neural response pattern for this stimulus. Reference to Fig. 24 shows three

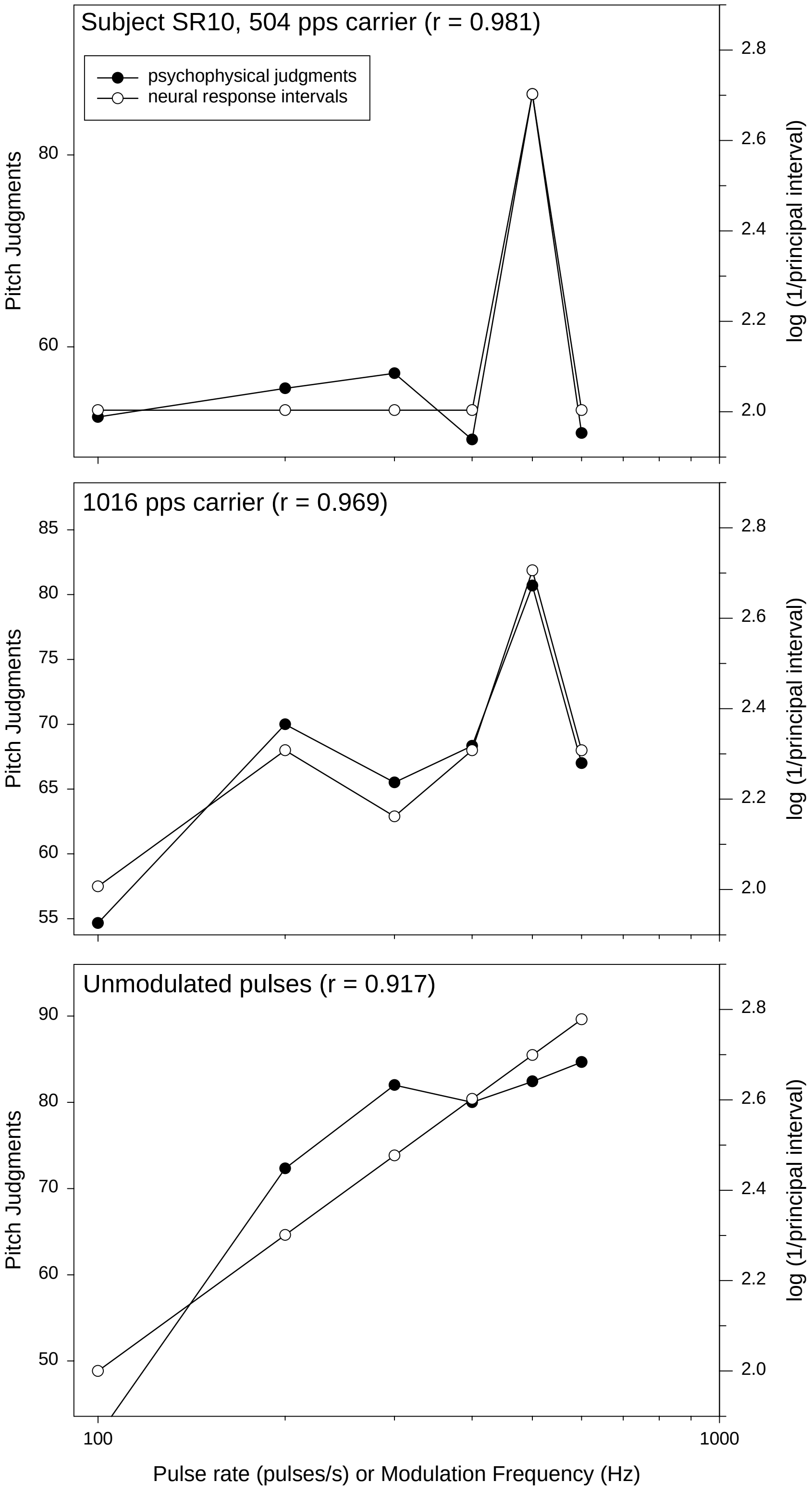


Fig. 39. Comparisons of psychophysical judgments versus intervals between principal peaks or events in the neural response patterns for the same stimuli, subject SR10.

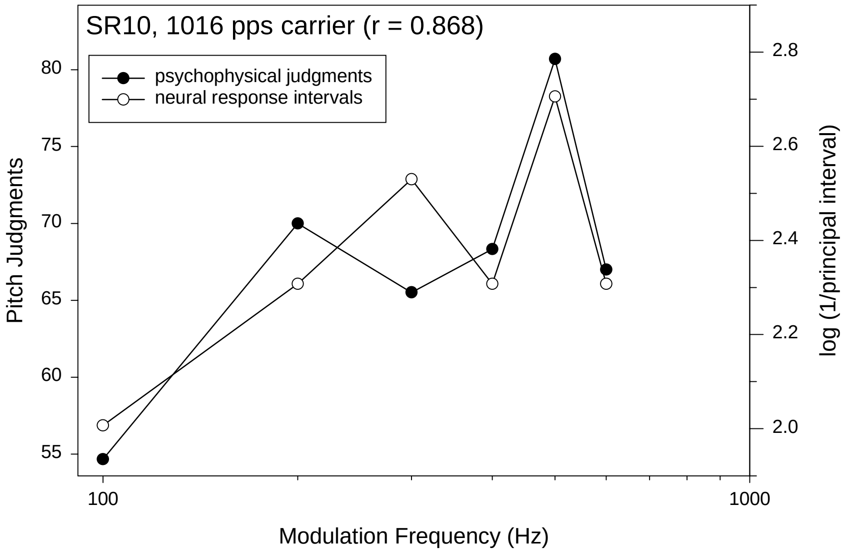


Fig. 40. Comparisons of psychophysical judgments versus intervals between principal peaks or events in the neural response patterns for the same stimuli, subject SR10, using an alternative set of intervals for the 1016 pulses/s conditions.

intervals with high correlations in the autocorrelation function for the neural response pattern. The highlighted interval is the one used for the present comparison in Fig. 35. However, the other two intervals have quite high correlation values and could contribute to the overall percept. Each of these intervals (7 and 10 ms) is longer than the highlighted interval (3 ms), and therefore might produce a reduction in perceived pitch.

Results for SR3 (Fig. 36) are generally similar to those of SR2. High correlations again are found for each of the three types of stimuli. The correlation for the 504 pulses/s carrier conditions is significant at $p < 0.002$, and the other two correlations are significant at $p < 0.001$.

Like SR2, SR3 shows a difference between perceptual and neural data points for 300 Hz modulation of the 1016 pulses/s carrier. The explanation offered above for SR2 also might apply for SR3. Both subjects show a multiplicity of (the same) intervals in their neural response patterns for this condition.

In addition, SR3 shows a relative elevation in pitch judgments for 200 and 300 Hz modulation of the 504 pulses/s carrier (top panel of Fig. 36). Inspection of Fig. 26 indicates multiple intervals in the response patterns for these two conditions. Although the correlation at 10 ms in the autocorrelation functions for each stimulus is substantially higher than the correlations for other intervals, the correlations at 4 and 6 ms are nonetheless significant ($p < 0.05$ and $p < 0.005$, respectively) for the 200 Hz modulation condition and the correlation at 4 ms is nonetheless significant ($p < 0.01$) for the 300 Hz modulation condition. The presence of these shorter intervals may produce an increase in perceived pitch relative to the 100 and 600 Hz modulation conditions, which have only the 10 ms interval in their neural response patterns.

If the presence of multiple intervals indeed affects pitch judgments for SR3, we must note that presence of the same multiple intervals does not affect the judgments reported by SR2 (compare Figs.

23 and 26 – they show almost identical patterns of response for SR2 and SR3 across all conditions, including the 200 and 300 Hz conditions). Perhaps SR3 is more affected by the presence of multiple intervals than SR2, or, alternatively, SR2 is somehow able to ignore to at least some extent the presence of "secondary" intervals in making his judgments.

A final aspect of the results for SR3 is that her pitch judgments saturate at 500 pulses/s for the unmodulated pulse train conditions, as noted above. This saturation does not have a strong effect on the correlation of perceptual and neural data, however, as it affects only one of the six points.

Subject SR9 also exhibits a high correlation for the 504 pulses/s carrier conditions (Fig. 37, top panel; $p < 0.001$). However, the correlations for the 1016 pulses/s carrier conditions (middle panel) and for the unmodulated pulse trains (bottom) are substantially lower than the correlations for SR2 and SR3. The correlations for SR9 are significant, but only at the $p < 0.05$ level.

The largest discrepancy between perceptual and neural data for SR9 is in the differences in the patterns of the two for the unmodulated pulse train conditions (bottom panel of Fig. 37). The perceptual judgments show a saturation and then a decrement in pitch at and beyond 300 pulses/s. In contrast, the neural data show a progressive reduction in the interval between approximately uniform evoked potentials as pulse rate is increased. The representation of intervals in the auditory nerve responses is good for SR9, but her perception based on that afferent input does not follow those intervals, at least for pulse rates above 300/s.

As noted above, SR9 perceives 300 Hz modulation of the 1016 pulses/s carrier as being lower in pitch than 200 Hz modulation of that carrier (see middle panel of Fig. 37). This is a reversal of the patterns observed for SR2 and SR3, which show increases in pitch for the these two subjects with the increase in modulation frequency. A comparison of autocorrelation functions for the 300 Hz modulation condition among subjects SR2 (Fig. 24), SR3 (Fig. 27) and SR9 (Fig. 30) shows that the correlation for the identified interval of 3 ms is lowest for subject SR9. In addition, the correlation at 7 ms is relatively high for SR9 compared to the correlation at 3 ms. The peak at 7 ms in the autocorrelation function may be more dominant than the peak at 3 ms for SR9.

To evaluate this idea, we plotted a comparison of perceptual and neural data using the interval of 7 ms, instead of 3 ms, for the 300 Hz modulation condition. This plot is presented in Fig. 38. Clearly, the agreement between perceptual and neural data is improved with this change. The correlation increases from 0.841 to 0.910, and the significance level improves to $p < 0.02$, in the plot of Fig. 38.

An alternative interpretation of this last result is that SR9 can only perceive changes in intervals when the intervals are longer than about 3-4 ms. This interpretation is consistent with the results reviewed above for the unmodulated pulse trains (i.e., the saturation of judgments at 300 pulses/s). The interpretation also is consistent with the idea that, while both 3 and 7 ms intervals are strongly represented in the neural responses to 300 Hz modulation of the 1016 pulses/s carrier, only the 7 ms interval is perceived. In this interpretation, the central nervous system cannot utilize intervals present in auditory nerve responses that are shorter than 3-4 ms.

We note that the increases in pitch for 500 Hz modulation of the 504 and 1016 pulses/s carriers do not necessarily indicate that SR9 can perceive a 2 ms interval. Instead, she may be able to perceive either (1) effects of the gross sampling artifacts produced with these combinations of modulation frequency and carrier rates or (2) the difference between an interval that is longer than 3-4 ms and an interval that is shorter than 3-4 ms. In the results for the 504 pulses/s carrier, for example, the difference in the judgment for the 500 Hz modulation condition compared with the judgments for all remaining conditions merely would require that the subject perceive the difference between the strongly represented interval of 10 ms for 5 of the 6 conditions and something shorter, for the 500 Hz modulation condition.

Results for SR10 (Fig. 39) show relatively strong correlations for the SAM pulse train conditions. Note that for the 1016 pulses/s carrier conditions, the principal interval identified in the neural response pattern for 300 Hz modulation was 7 ms (Fig. 33) instead of the 3 ms identified for the other subjects (Figs. 24, 27 and 30). This choice produces a correlation of 0.969 in the comparison of perceptual and neural data ($p < 0.002$), whereas a choice of the 3 ms interval would produce a correlation 0.868 ($p < 0.05$), as shown in Fig. 40.

SR10 also has relatively low judgments of pitch for the 400 and 600 Hz modulation conditions with the 504 pulses/s carrier. These judgments may have been influenced by the presence of repeating groups in the neural response patterns for these stimuli, as described above. The intervals between the repeating groups are much longer than the maximum of 12 ms that would be demonstrated in the present autocorrelation functions.

As with SR9, SR10's judgments appear to asymptote at 300 pulses/s for the unmodulated pulse train conditions. However, intervals shorter than the reciprocal of 300 pulses/s are well represented in the neural response patterns for higher rates of stimulation for both subjects. Pitch does not increase for either subject with reductions in intervals below 3-4 ms.

Discussion

Results presented in this report demonstrate that increases in carrier rate for SAM pulse trains increases the range over which modulation frequencies are simply represented in patterns of auditory nerve responses to the stimuli. Perception of modulation frequency is strongly correlated for some subjects with intervals between principal peaks or events in the auditory nerve responses, at least for intervals greater than about 1-2 ms. For other subjects such correlations are not observed over the same range of intervals, and this suggests a limitation for them in the central processing of the afferent auditory nerve input. This idea is consistent with an interpretation presented by Blamey *et al*. (1996; 1997), that "central processing may account for a substantial part of the observed variance" in outcomes among implant patients. In our studies, subjects who had limited access to intervals present in the auditory nerve responses also had either moderate or extraordinarily low speech reception scores. Subjects who had good access had excellent to "superstar" levels of speech reception. More subjects need to be included in our studies to evaluate the possibility of a significant correlation between abilities to utilize intervals in the auditory nerve responses versus speech reception scores.

The total range of pitch judgments was increased for all subjects except SR15 with increases in the carrier rate for SAM pulse trains up to 5081 or 10162 pulses/s. Thus, there may be some benefit associated with the use of high carrier rates even for subjects who have limited or no access to modulation frequencies above 200 or 300 Hz. For subject SR9, for example, use of the 10162 pulses/s carrier would increase the difference in pitch percepts for the 100 and 200 Hz modulation conditions compared with the other tested carrier rates.

Increases in carrier rates for subjects at the other end of the performance spectrum may confer much greater benefits. For subjects SR2 and SR3, use of a 5081 or 10162 pulses/s carrier allows monotonic scaling of modulation frequencies up to 500 Hz for SR3 and up to at least 600 Hz for SR2.

To explore the limits of SR2's abilities, we conducted an additional scaling experiment in which the range of modulation frequencies and pulse rates was extended to 1400 Hz or 1400 pulses/s, respectively. The results are presented in Fig. 41 and Table 9. A peak in judgments is observed at 1000 Hz modulation for the 2032 and 5081 pulses/s carriers, as might be expected from the previous findings. In contrast, judgments increase monotonically over the entire range of modulation frequencies with the 10162 pulses/s carrier. Not all of the differences between adjacent modulation frequencies are significant; however, all judgments for modulation frequencies at least two steps apart are significant. There is no evidence of a saturation in judgments with the 10162 pulses/s carrier, even out to the modulation frequency of 1400 Hz.

In contrast, judgments for the unmodulated pulse trains saturate at 1000 pulses/s. This shows that access to rate or frequency information may be greater with SAM pulse trains using high carrier rates than with unmodulated pulse trains. This is consistent with the idea that the high carriers rates elicit in the nerve a spontaneous-like pattern of neural activity, which can support the representation of relatively high modulation frequencies (see QPR 7; Wilson *et al.*, 1994; Wilson, 1997; Wilson *et al.*, in press; and Parnas, 1996).

Access to frequencies as high as (or higher than) 1400 Hz on single channels in a multichannel processor may support large improvements in speech reception performance, especially under adverse listening situations, for subjects like SR2. We will be evaluating this possibility in future studies.

For subjects who still do not enjoy high levels of speech reception even under quiet conditions, the present results suggest that a small gain might be realized through use of high carrier rates, i.e., such use would be expected in most cases to increase the range of pitch judgments for low modulation frequencies. However, such use would not be expected to increase the observed saturation in judgments as modulation frequency is increased above a certain (relatively low) point.

Although some gain may be realized for subjects in this category with increases in carrier rate, greater gains might be produced with processor manipulations that emphasize the spatial (across electrodes) representation of speech stimuli at the expense of the temporal representation (for individual electrodes). That is, these subjects show a basic limitation in access to representations of temporal events at the auditory nerve. It may be better for them to acknowledge this and apply tradeoffs that might improve their perception of spatial cues.

We have conducted preliminary studies with SR9 to evaluate processing options that might emphasize the representation of spatial cues, while perhaps not harming or harming greatly her perception of modulation frequencies up to somewhere in the region of 200 Hz. The manipulations have included use of especially low carrier rates (e.g., 417 and 500 pulses/s), to minimize temporal channel interactions, and large (up to 50 percent) decreases in target thresholds for the mapping functions, also to minimize deleterious effects of temporal channel interactions. Large increases in speech reception scores were obtained for her with these manipulations. Additional studies are planned for her and other patients in her category to evaluate such tradeoffs between spatial and temporal representations further.

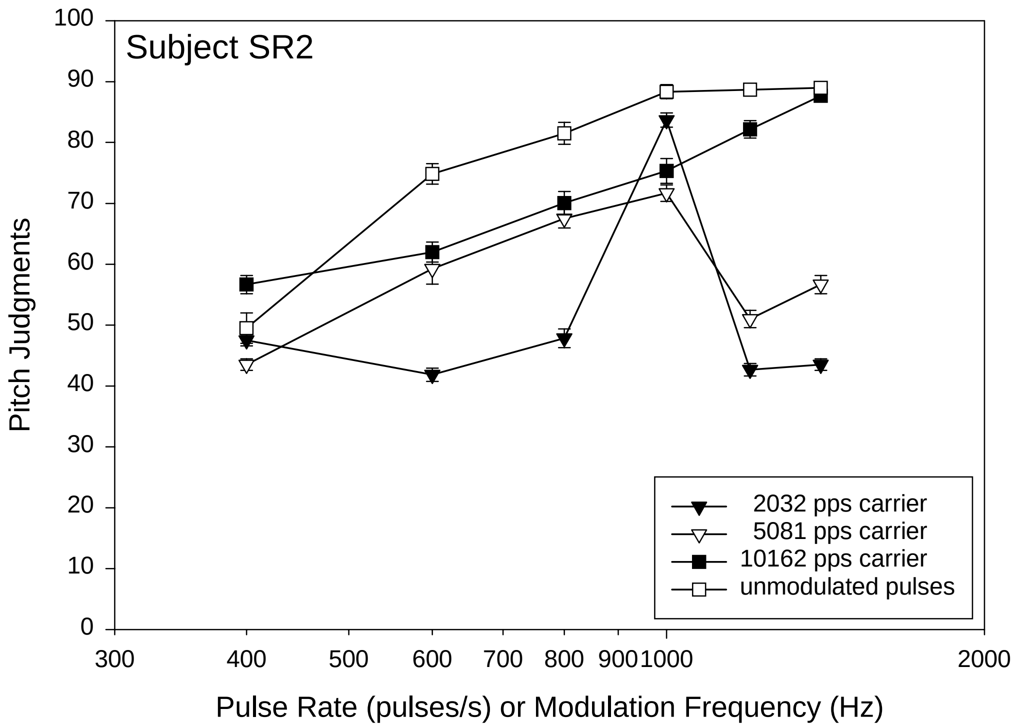


Fig. 41. Scaling results for subject SR2, high modulation frequencies for SAM pulse trains and high pulse rates for unmodulated pulse trains. Bars show standard errors of the mean.

Table 9. Significant differences among conditions for the various stimulus types in the scaling experiment for subject SR2, using high modulation frequencies for SAM pulse trains and high pulse rates for unmodulated pulse trains (see Fig. 41).

Stimulus type	Significant differences among conditions
2032 pps carrier	Judgment for 1000 Hz mod > judgments for all other mod frequencies Judgments for 400 and 800 Hz mod > judgments for 600 and 1200 Hz mod
5081 pps carrier	Judgments for all mod frequencies different except for 600 *versus* 1400, 800 *versus* 1000 and 1200 *versus* 1400 Hz mod
10162 pps carrier	Judgments for all mod frequencies different except for 400 *versus* 600, 800 *versus* 1000 and 1200 *versus* 1400 Hz mod
unmodulated pulses	Judgments for all pulse rates different except for 1000 *versus* 1200, 1000 *versus* 1400 and 1200 *versus* 1400 pps

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III. Plans for the Next Quarter

Our plans for the next quarter include the following:

- Presentation of project results in four invited lectures, including three at the 1997 Conference on Implantable Auditory Prostheses (August 17-21) and one at the 28th Annual Neural Prosthesis Workshop (October 15-17).
- Ongoing studies with Ineraid subject SR2 (usually one morning per week). Studies anticipated for the next quarter include (a) psychophysical and electrophysiological measures like those described in this report and QPR 7, but with different stimulus conditions; (b) continued measures of intracochlear EPs with high rate stimuli; and (c) completion of speech reception measures with CIS processors using different numbers of channels and various channel to electrode assignments (most of the remaining conditions involve processors with 1, 2 or 3 channels).
- Continued preparation for studies with recipients of bilateral implants, including verification of correct operation of an interface system the University of Innsbruck and we have developed for simultaneous laboratory control of two Med El receivers. The verification will be conducted with a local Med El patient (ME1, scheduled to visit the laboratory September 18), who will compare signals among those provided by his implant system, by our laboratory system using the interface for one transmitting antenna, and by our laboratory system using the interface for the other transmitting antenna.
- Initiation of studies with subject ME2 (October 27 to November 14), who has full insertions of Med El COMBI 40 implants on both sides. This subject will be visiting us from Germany and will be tested using German language test materials. He will be accompanied by Stefan Brill from the University of Innsbruck, who will serve as a Guest co-investigator for these studies. We also will be assisted by consultant Sigfrid Soli, who will be with us for the week beginning November 3. Dr. Soli is an internationally recognized authority on binaural processing and on measures of speech reception, for both unilateral and bilateral stimulation. He and Dr. Michael Nilsson, also with the House Ear Institute in Los Angeles, incorporated German language test materials into a system they have developed for use in studies of binaural signal processing and perception. That system, with those incorporated materials, will be used in the studies with ME2. Dr. Joachim Müller, from the Julius-Maximilians-Universität in Würzburg, Germany, also will be visiting us for the last two weeks of studies with ME2. Dr. Müller was the implanting surgeon for ME2.
- Studies with Ineraid subject SR3 (September 25 to October 1), for additional EP measures and for evaluation of CIS strategies as implemented in the processor for the new CI24M device.
- Studies with Ineraid subject SR10 (October 2-11), for a variety of continued psychophysical, evoked potential, and speech reception measures.
- Continued development of the evoked potentials and speech reception laboratories.
- Continued analysis of speech reception and evoked potential data from prior studies.
- Continued preparation of manuscripts for publication.

IV. Acknowledgments

We thank subjects SR2, SR3, SR9, SR10, SR15 and SR16 for their participation in the studies of this quarter.

Appendix 1. Summary of Reporting Activity for this Quarter

Reporting activity for the last quarter, covering the period of May 1 through July 31, 1997, included the following:

Invited Presentations

Wilson BS: Possibilities for the further development of speech processor designs. *Vth International Cochlear Implant Conference*, New York, NY, May 1-3, 1997.

Lawson DT, Wilson BS, Zerbi M, Roush PA, van den Honert C, Finley CC, Tucci DL, Farmer JC Jr: Within patient comparisons among processing strategies for cochlear implants. *130th Annual Meeting of the American Otological Society,* Scottsdale, AZ, May 10-11, 1997 (lecture presented by Wilson).

Lawson DT, Wilson BS, Zerbi M, van den Honert C, Finley CC, Farmer JC Jr, McElveen JT, Roush PA: Bilateral cochlear implants controlled by a single speech processor. *130th Annual Meeting of the American Otological Society*, Scottsdale, AZ, May 10-11, 1997.

Wilson BS: Design of speech processors for cochlear prostheses. Johns Hopkins University, Department of Biomedical Engineering, May 30, 1997.

Additional Presentation

Tucci DL, Roush PA, Lawson DT, Wilson BS, Zerbi M: Modified percutaneous Nucleus cochlear implant: Surgical experience and speech recognition results. *Vth International Cochlear Implant Conference*, New York, NY, May 1-3, 1997.