

HEARES 01803

## Short Communication

# Electrical stimulation of the auditory nerve: Effects of pulse width on frequency discrimination

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Effects of pulse width on discrimination of simultaneous changes in frequency and level of electrical pulse trains were studied in a monkey subject with a cochlear implant. At test-stimulus levels where performance was minimum, frequency difference limens were larger for longer-duration pulses than that for shorter-duration pulses. Several factors may have contributed to these differences.

Auditory prosthesis; Psychophysics; Electrical stimulation; Nonhuman primate; Frequency discrimination; Level discrimination

## Introduction

Cochlear prostheses offer profoundly deaf patients a semblance of hearing, although performance with these devices is highly variable and probably depends upon many different factors such as patient ability, coding strategies, electrode configuration, etc. Some of the most promising research directed toward increasing speech perception is in the area of coding strategies.

Recordings from single auditory nerve fibers have shown how single fibers respond to acoustic and electrical signals, in turn giving insight about what specific coding strategies may prove most useful. Psychophysical studies are needed to see how the entire auditory system responds to electrical stimuli and to test the effectiveness of the coding strategies.

There are several lines of evidence that responses to long-duration electrical pulses are distinctly different from those for shorter-duration pulses. Electrophysiological data suggest that the across-fiber distribution of response times is greater for long-duration pulses than for short-duration pulses (van den Honert and Stypulkowski, 1987). In individual fibers, long phase duration signals can elicit multiple spikes in the most effective phase of the cycle and or spikes in both phases, while shorter phase duration signals tend to produce a maximum of one spike per cycle (Hartmann et al., 1984; Javel et al., 1987; Parkins, 1989; van den Honert and Stypulkowski, 1987). Psychophysical studies show

differences in slopes of threshold vs pulse duration functions and threshold vs frequency functions which are phase duration dependent, suggesting a different response to pulses greater than 1 ms/phase as compared to those less than 0.5 ms/phase (Pfingst et al., 1991; Shannon, 1985).

The hypothesis investigated in this study was that the subject's ability to discriminate changes in the frequency of a pulse train would be dependent on the waveform of the pulses. Specifically we hypothesized that difference limens for long-duration pulses would differ from those obtained when short-duration pulses were used. We chose to study pulses spanning the range, from greater than 1 ms/phase to less than 0.5 ms per phase, over which distinct differences in detection threshold functions have been seen.

Changes in the frequency of electrical stimulation of the auditory nerve can give rise to changes in both the perceived pitch and the perceived loudness of the signal (Shannon, 1985). Changes in level can also affect perceptions of both loudness and pitch (Townshend et al., 1987). Discrimination of changes in the frequency of an electrical signal can be affected by simultaneous small changes in level, and it is possible to find a level change for which the performance is minimum (Pfingst and Rush, 1987; Pfingst and Rai, 1990). Performance at this test-stimulus level is of interest because in normal environmental signals, frequency and level changes are often not correlated. Thus there may be some levels for which detection of a change in frequency is poorer than at others. In this study we examined the discrimination of frequency changes both with and without small changes in the test-stimulus level.

## Methods

The subject was an adult male bonnet monkey (*Macaca radiata*), implanted with electrodes in the right cochlea. The cochlea was deafened with Neomycin at the time of implantation. For this experiment we used monopolar stimulation of an electrode in the basal turn of the scala tympani. The scala tympani electrode was one of 6 spherical platinum-iridium electrodes mounted on the surface of a Silastic rubber carrier (see Fig. 6 in Xue and Pfingst, 1989). The electrode used in this experiment was located approximately 4 mm inside the round window. The reference electrode was a stainless steel wire imbedded in the temporalis muscle. Data for this experiment were collected about 21 months after implantation, and after a long period of threshold stability. Threshold levels for low-frequency sinusoids for this implant were in the middle to high range, relative to those for other implants in monkeys with known nerve survival patterns (Pfingst et al., 1985), suggesting moderate to poor nerve survival in this case.

The subject was trained for psychophysical tasks by using positive-reinforcement operant-conditioning techniques. Once the subject was trained, test sessions proceeded as follows. The subject initiated each trial by depressing a telegraph key in the presence of a trial-ready light. The key press initiated a randomly variable (1 to 6 second) foreperiod. Key releases during this foreperiod resulted in a penalty time out and terminated the trial. If the key remained pressed, the foreperiod was followed by a 1 s observation period that was marked only by the presence of the auditory stimulus and was unmarked on catch trials. Key releases during the observation interval (i.e. within 1 s of stimulus onset) on stimulus trials constituted a correct response. These responses were reinforced by delivery of 0.2 cc of applesauce. The method of constant stimuli was used for all experiments. Stimulus tables were constructed so as to maintain a relatively constant rate of reinforcement across conditions in order to avoid conditions that might lead to a change in response strategy.

For threshold determinations, the auditory stimulus was an electrical current to the implanted electrodes, and no signal was presented on catch trials. Percent correct responses (releases within 1 s of stimulus onset) were plotted as a function of test-stimulus level to form psychometric functions based on twenty trials per stimulus level. Threshold was defined as the level (determined by interpolation) at which responses were obtained on 50% of the trials.

Guess rates (percent releases during the 1 s unmarked observation period on trials where no stimulus was presented) were measured during all sessions. We attempted to keep the guess rate constant by control-

ling the duration of a penalty time out, contingent on early releases. With this method, guess rates were usually kept within a range of 2% to 15% and did not vary systematically across conditions. If these criteria for the guess rate were not met, the data were not used and additional training was carried out.

Dynamic ranges were estimated using reaction times which, in well trained subjects, have been shown to vary systematically with stimulus loudness under a variety of conditions (Moody, 1970; Pfingst et al., 1975, 1979). Reaction times equivalent to those produced in response to a 100 dB SPL acoustic white-noise stimulus to the subject's normal-hearing ear were used as a criterion for the upper limit of the dynamic range for the electrical stimuli (Pfingst et al., 1979).

Frequency and level difference limens were measured using a task similar to the threshold task described above except that a reference stimulus was presented during the variable foreperiod and a key release made within 1 s after the stimulus changed comprised a correct response. For the discrimination task, repeating stimuli (200 ms on and 100 ms off) were used. Changes in the frequency and attenuator settings always occurred during one of the periods when the stimulus was off, and with no change in the duration of this period. In the frequency discrimination tasks the initial stimulus was a pulse train at 100 pps and the test stimuli differed from the reference stimulus in frequency, level, or both frequency and level. On catch trials, the reference and test stimuli were identical.

Pulse trains were created by a custom-built pulse generator that was controlled by a PDP 11/23 computer using software developed in-house. Signal level was controlled by a computer controlled Wilsonics (model PATT) attenuator. The resulting pulse train was used to drive a controlled-current stimulator, modified from the original design described by Spelman et al., (1978). The current was sent directly from the controlled-current stimulator to the electrodes in the subject's ear via a percutaneous connector.

The subject was tested using three different pulse widths; 0.25 ms/phase, 0.80 ms/phase, and 2.5 ms/phase. The pulses were symmetric charged-balanced biphasic rectangular pulses. Electrodes were connected so that the leading phase of the pulse going to the scala tympani electrode was negative. Thresholds and dynamic-ranges were determined for 200 ms duration pulse trains at 100 pps for each pulse width. Then rough estimates of the frequency difference limen were obtained at levels corresponding to approximately 90% of the dynamic range. Frequency and level discrimination studies were then begun, with the final set of stimuli being those represented in Fig. 1. To arrive at the stimulus set represented in Fig. 1, pilot tests were conducted using these and other stimuli at nearby frequencies and levels. In particular, stimuli at

other levels near the level where performance was minimum, for each test-stimulus frequency, were tested. The purpose of these tests was to determine if a level could be found where performance was significantly worse than that seen at any of the other tested levels,

but none was found, so the final data collection involved the stimuli shown.

For the final data collection, individual sessions, each containing a subset of the total stimulus set were run in random order. The stimulus parameters in a given experimental session consisted of one of the pulse widths, two different test-stimulus frequencies, and the various test-stimulus levels depicted in Fig. 1, plus catch-trial stimuli. Stimuli were presented using the method of constant stimuli until 20 trials were collected for each stimulus. The subject ran two or three sessions each day until a total of 10 sessions were run for each condition.

## Results

Results for the three pulse widths are plotted in Fig. 1. This figure shows the percent responses at each test-stimulus frequency as a function of test-stimulus level re the reference stimulus level. For each test-stimulus frequency there was a test-stimulus level at which the percent responses to the stimulus change was minimum. For the 0.8 ms/phase pulses, these minima were all at the level that was equal to the reference-stimulus level (i.e. 0 dB re reference stimulus level). This was also the case for the 0.25 ms/phase pulses except at the test-stimulus frequency of 111 pps. However, for the 0.25 ms/phase pulses, there was an asymmetry in the percent-responses-versus-level functions for all of the test-stimulus frequencies with the percent responses at 0.5 dB below the reference-stimulus level being lower than those at 0.5 dB above the reference-stimulus level. For the larger frequency changes (test-stimulus frequencies of 108 pps and above), the percent responses at 0.5 dB below the reference-stimulus level were similar to those at the reference stimulus level. A slight asymmetry was also seen in the percent-responses-versus-level function for the test stimulus at 100 pps, which equaled the reference stimulus in frequency. For the 2.5 ms/phase pulses, the asymmetry was marked with the minimum

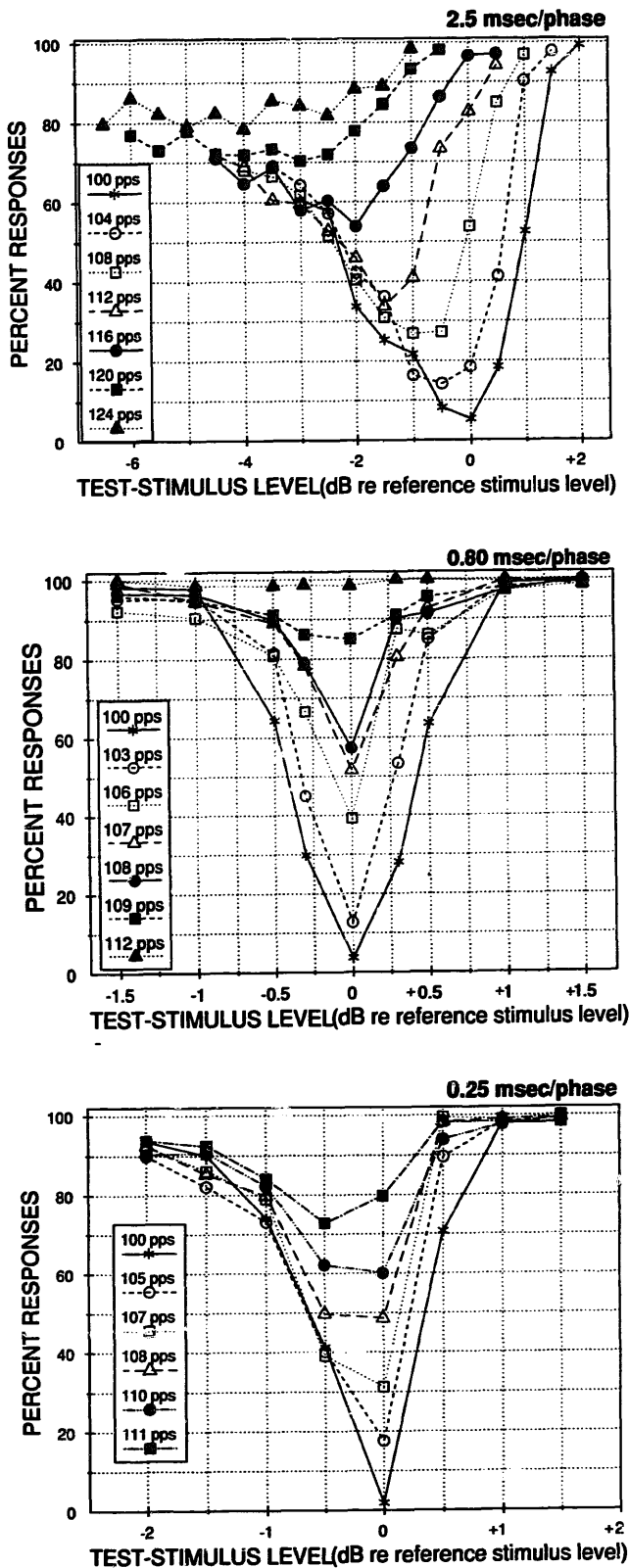


Fig. 1. Percent-responses-versus-test-stimulus-level functions for the three pulse widths tested. Each graph shows the data for one pulse width as indicated at upper right corner of the graph. Each point gives the mean percent responses for one of the test stimuli based on 10 sessions at 20 trials per test stimulus per session. Each test-stimulus frequency is indicated by a unique symbol and test-stimulus levels are indicated on the abscissa. The reference-stimulus frequency was 100 pps. Thus, the test stimuli indicated by stars differed from the reference stimulus only in level, except for the test stimulus at 0 dB re the reference-stimulus level, which was identical to the reference stimulus. Of the remaining test stimuli, those at 0 dB re the reference-stimulus level differed from the reference stimulus only in frequency, while all of the remaining test stimuli differed from the reference stimulus in both frequency and level.

TABLE I

Frequency and level difference limens

Pulse Width (ms/phase)	Frequency Difference Limens (pps)	Level Difference Limens (increasing) (dB)	Level Difference Limens (decreasing) (dB)
2.5 (●)	15.2	0.96	2.34
2.5 (○)	7.6		
0.80	6.9	0.42	0.42
0.25	8.3	0.35	0.63

The frequency difference limens are based on the psychometric functions shown in Fig. 2 and the symbols correspond to those in Fig. 2. The level difference limens are based on the functions shown by the stars in Fig. 1.

percent responses occurring at increasingly lower test-stimulus levels as the test-stimulus frequency was increased. For this pulse width there was also a marked asymmetry in the level-difference limens: 2.34 dB for decreases in level and 0.96 dB for increases (Table I).

The minimum percent responses for each of the percent-responses-versus-test-stimulus-level functions were used to construct psychometric functions, which are shown in Fig. 2. In addition, Fig. 2 shows the percent responses to test stimuli at 0 dB re the reference-stimulus level for the 2.5 ms/phase pulses. Frequency difference limens, calculated from these functions by interpolation as the frequency difference corresponding to a 50% response rate, are given in Table I. Also given in Table I are the level difference limens

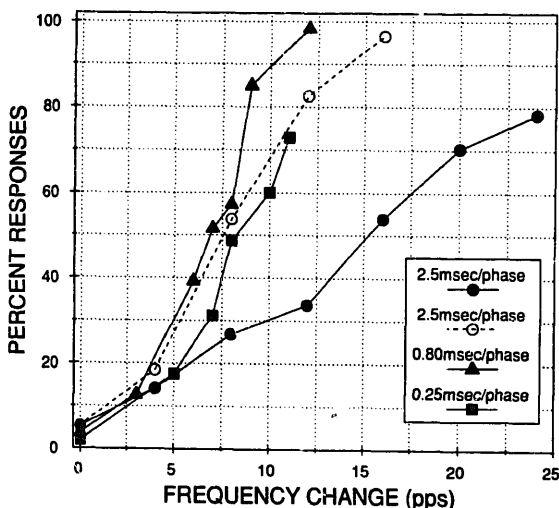


Fig. 2. Percent responses (key releases) made to test stimuli during the 1 s observation periods. 'Frequency change' is the difference between the reference-stimulus frequency and the test-stimulus frequency. The solid symbols indicate percent responses at the test-stimulus levels at which the percent responses was minimum in the functions shown in Fig. 1. The open symbols indicate percent responses when the test-stimulus level equaled the reference-stimulus level.

from the psychometric functions for the 100 pps test stimuli in Fig. 1.

## Discussion

This experiment demonstrated a clear effect of pulse width on discrimination of simultaneous frequency and level changes as well as on discrimination of level changes alone. There was relatively little effect of pulse width on discrimination of frequency changes alone for the particular parameters studied here, though the weight of evidence suggests that these frequency discrimination results depended on different cues for the different pulse widths, as discussed below.

In this experiment we identified the test-stimulus levels, relative to the reference stimulus levels, at which performance was minimum for each frequency change. For the 2.5 ms/phase pulses, these levels decreased systematically as a function of the test-stimulus frequency, while for the other two pulse widths the minima were at or very near the reference-stimulus level. The effects of test-stimulus level on frequency discrimination could be due to several mechanisms including elimination of loudness cues introduced by the frequency change, changes in pitch associated with changes in level (Townshend et al., 1987), or decreases in frequency discrimination ability which typically accompany decreases in stimulus level (Pfingst and Rai, 1990). One or more of these mechanisms may have also contributed to the asymmetry in the percent-responses-versus-level functions seen for some of the pulses in this study.

It is difficult to distinguish among the mechanisms affecting loudness and pitch, even in human subjects, since very small changes in loudness and pitch are difficult to distinguish reliably. These distinctions, however, have to do with definitions of loudness and pitch, which it was not our purpose to resolve. Rather, we were interested in knowing if changes in the frequency of stimulation could be discriminated despite associated changes in the level of the signal. In signals used in cochlear prostheses, unless level and frequency are correlated, there will be some combination of those variables, occurring naturally, at which performance will be minimum, and it is that minimum performance that we have measured in these experiments. Based on this minimum-performance analysis, frequency discrimination for the longer-duration pulse was worse than that for the two shorter pulses.

The fact that frequency discrimination for the 2.5 ms/phase pulses was degraded by small changes in level, while those for the shorter pulses were degraded very little or not at all, is not surprising, since loudness (at least near threshold) is affected by frequency more for long-duration pulses than for short-duration pulses

(Shannon, 1985; Pfingst and Morris, 1992). It is likely that at least part of the degradation in performance at levels slightly below the test stimulus level was due to the reduction or elimination of loudness cues and that the performance at the level equal to the reference stimulus level for these pulses was facilitated by loudness cues.

Frequency discrimination is known to depend on the level of the reference stimulus and there is no obvious way to match reference stimulus levels for stimuli that have different thresholds and dynamic ranges. Testing at equal positions in the dynamic range is a commonly used, practical, approach. We studied effects at a relatively high level in the dynamic range. This should minimize level-dependent differences between the pulses relative to those that might be found if the stimuli were studied at equal-current levels or at low levels.

The observation that level difference limens for the 2.5 ms/phase pulses were larger than those for the shorter pulses is consistent with earlier studies which showed larger level-difference limens for low-frequency (long-phase-duration) sinusoidal stimuli as compared to higher frequency (shorter-phase-duration) stimuli (Pfingst et al., 1983).

The data from this experiment, coupled with electrophysiological studies of responses to pulsatile or continuous stimuli of various phase durations, suggest the hypothesis that the more temporally precise responses to shorter phase duration signals lead to better discrimination of changes in signal frequency. However, other stimulus-dependent features of the neural response patterns could also account for these differences in the psychophysical discrimination. More detailed comparisons of electrophysiological and behavioral measures, obtained using identical stimuli, preferably with both measures obtained from the same animal, are needed to test these hypotheses.

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