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Effects of level on nonspectral frequency difference limens for electrical and acoustic stimuli

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The purpose of this experiment was to study the effects of stimulus level on discrimination of frequency as represented in the temporal waveforms of acoustic and electrical signals. The subjects were four nonhuman primates in which one ear had been deafened and implanted with an electrode array and the other ear was untreated. Frequency difference limens for 100 Hz electrical sinusoidal stimulation via a cochlear implant in the deafened ear were compared to those for 100 Hz sinusoidally amplitude-modulated white noise (SAM noise) acoustic stimuli to the normal-hearing contralateral ear. To correct for loudness cues, levels of the test stimuli were varied relative to the reference-stimulus level. The test-stimulus levels at which the percent responses were minimum were determined. These levels were used to measure the frequency difference limens. Frequency difference limens for the electrical stimuli decreased as a function of reference-stimulus level through most of the dynamic range, while those for the acoustic stimuli reached a minimum at 20 dB to 40 dB above threshold. For the electrical stimuli the slopes and relative positions of the frequency difference limen vs. level functions varied from subject to subject, and with changes in electrode configuration within a subject. These differences were related to threshold level and dynamic range. At higher levels of stimulation, frequency difference limens for acoustic and electrical stimuli fell in the same range. The slopes and relative positions of the frequency difference limen vs. level functions for electrical stimuli did not parallel those of level difference limen vs. level functions collected simultaneously from the same ears. The data suggest that nonspectral frequency discrimination may depend on the number of nerve fibers stimulated. With prostheses in cochleas with less than a full complement of auditory nerve fibers, the data suggest that stimulation level is an important variable influencing discriminability.

Frequency discrimination; Level; Amplitude modulation; Auditory prosthesis; Electrical stimulation; SAM noise; Psychophysics; Nonhuman primate

Introduction

Auditory prostheses rely on direct electrical stimulation of the auditory nervous system to produce sensations of sound. Multichannel prostheses may use temporal codes, place codes, or both to convey frequency information. The place codes are intended to mimic the normal representation of the spectral information in acoustic signals which, in the normal ear, are processed by the cochlea to form a spatial representation of frequency along the length of the cochlear partition. The temporal codes rely on phase locking by auditory nerve fibers to low frequency temporal features (events per unit time) in the signal's waveform. Single channels of auditory prostheses use only the temporal codes to represent frequency. The focus of this study was on the ability of subjects to discriminate frequency changes coded by temporal rather than place codes. In particular, we looked at the effects of stimulus level on this nonspectral frequency discrimination in the 100 Hz frequency region. Several analog auditory-prosthesis signal processors rely on temporal coding of frequency in this region to transmit information about the fundamental frequency of the voice (e.g. Fourcin et al., 1984; Clark, 1986). Nonspectral frequency difference limens and other measures of temporal resolution indicate that a subject's abil-

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ity to follow temporal changes in signals typically deteriorates above 100 Hz (Viemeister, 1979; Formby, 1985; Pfingst, 1985; Shannon, 1986).

Nonspectral frequency discrimination may be studied by electrically stimulating cochleas that have been deafened by destroying the hair cells, since these cochleas lack the normal ability to analyze the signal's spectral content. Another approach is to use acoustic stimuli that contain no spectral cues about frequency. One of the best signals for this purpose is sinusoidally amplitude-modulated white noise (SAM noise; Burns and Viemeister, 1976, 1981; Formby, 1985). Since the spectrum of this signal contains all of the frequencies and levels present in the noise carrier, sidebands which characterize the spectrum of amplitude-modulated signals will also be present at all frequencies and levels. Thus they will carry no discriminable spectral information about the modulation frequency of the signal. Changes in the modulation frequencies of these signals must be discriminated on the basis of temporal cues in the envelope of the signal.

A basic question relevant to theories of frequency discrimination is whether the temporal cues present in markedly different signals, such as electrical sinusoids and acoustic SAM noise signals, are functionally equivalent. Does the mode of presentation of the temporal information affect the discrimination? In practical terms, Pierce and Zweig (1975) and Viemeister and Wakefield (1985) have proposed that acoustic SAM noise might be an appropriate signal for studies relevant to electrical stimulation of single channels of auditory prostheses.

Neurophysiological studies of the responses of auditory nerve fibers to sinusoidal electrical signals have shown that single auditory nerve fibers follow the frequencies of the electrical sinusoids in a manner analogous to the phase-locked response to acoustic stimuli. Studies of the phase-locked neural responses to low-frequency sinusoidal electrical stimuli (Glass, 1984; Hartmann et al., 1984; van den Honert and Stypulkowski, 1987) have demonstrated several level-dependent characteristics that are analogous, although not identical, to those seen with acoustic stimulation: 1) low thresholds for synchronization relative to the discharge-rate thresholds, 2) rapid growth of the synchronization index as a function of level, and 3) recruitment of additional fibers as level is increased above the thresholds of the lowest-threshold fibers. The third characteristic is implied by the observed variation in thresholds across fibers.

Studies from a number of laboratories have demonstrated that single auditory nerve fiber discharge patterns follow the frequency of the envelopes of acoustic amplitude-modulated tones (Javel, 1980; Palmer, 1982; Smith and Brachman, 1980; Yates, 1987). Studies at the cochlear nucleus indicate that this envelope frequency following also applies to amplitude-modulated noise signals (Møller, 1972). The maximum envelope frequency that neurons are capable of following decreases at higher centers in the auditory pathway, but following of envelope frequencies has been seen for frequencies as high as 200–500 Hz in inferior colliculus (Rees and Møller, 1987; Langner and Schreiner, 1988) and as high as 100 Hz in auditory cortex (Schreiner and Urbas, 1986).

In order to better understand the perceptual correlates of these characteristics of the auditory nerve responses to electrical and acoustic stimuli, we have measured psychophysical frequency-difference limens for acoustic and electrical stimulation as a function of stimulus level. In previous studies of frequency discrimination for electrical stimuli, effects of level have been largely ignored. Most studies in humans (e.g. Fourcin et al., 1984; House and Edgerton, 1982; Müller, 1981; Merzenich et al., 1973; Simmons, 1966) have been conducted only at the most comfortable listening level or at unspecified levels. Bilger (1977) tested a few subjects at multiple sensation levels, but the results are mixed and their interpretation is complicated by differences in the subjects' signal processors. All of these studies have indicated that frequency difference limens are lowest at low frequencies and are often poor at frequencies above 300 Hz, but there is a large degree of variability in the data.

Effects of level on frequency discrimination with acoustic SAM noise signals has not been reported, but Viemeister (1979) has shown that level affects temporal modulation transfer functions for normal ears only near threshold.

One problem in studying the discrimination of frequency changes in electrical signals is that changes in stimulus frequency can have a marked effect on the loudness of a signal as well as its pitch. Loudness, of course, is also affected by stimulus level. When we study frequency discrimination, we are usually interested in separating the effects of the frequency change on pitch-like perceptions from the effects on level-dependent loudness-like perceptions. Efforts to accomplish this involve roving the level of either the reference (standard) stimulus or the test (comparison) stimulus or both in a series of small steps bracketing the presumed equal-loudness point. Variations of this technique have been used for discrimination of acoustic pure tones (Henning, 1966; Emmerich et al., 1989), electrical pulse trains (Herndon, 1981), and electrical sinusoids (Pfingst and Rush, 1987). None of these procedures allow complete and unambiguous separation of pitch and loudness cues, since pitch and loudness are both affected by frequency and level. However, they do allow specification of the minimum difference limen that can be attributed to a frequency change in situations where frequency and level vary simultaneously and are not correlated, as in most natural stimuli. If the test-stimulus level is varied on a trial-by-trial basis (but fixed on each trial) it is possible to determine the level at which performance is minimum (Pfingst and Rush, 1987).

In this paper we report on studies of frequency discrimination of electrical sinusoids as a function of level for a variety of electrode configurations in deafened and implanted monkeys. We also compared the performance using electrical stimuli with the performance of the same subjects stimulated in the nonimplanted ear with acoustic SAM noise signals. Finally, since nonspectral frequency discrimination depends on detection of periodic amplitude modulations in the signal, we compared frequency difference limens with level difference limens.

Methods

Overview

The subjects were 4 male macaques (3 *M. mulatta* and 1 *M. radiata*) ranging in age from 5 to 9 years at the time of testing. They were housed in individual primate cages except during training and testing sessions at which time they were seated in primate chairs. The subjects were trained using positive reinforcement operant conditioning procedures to perform psychophysical tasks that could be used to measure detection (absolute) thresholds, dynamic ranges, and frequency and level difference limens. They were tested for 1–3 h/day, 5 days/week.

The subjects were trained using acoustic stimuli and then were deafened in one ear and implanted with a multielectrode array in the scala tympani and/or in the cochlear wall. Following implantation, thresholds for electrical stimuli were measured as a function of time until stable and then frequency and level difference limens were measured until they stabilized. After the subjects had received a minimum of one month's training and testing on each of the relevant tasks and after all performance was stable, data collection was begun. The nonimplanted ear in these subjects was used for acoustic testing throughout the period of testing with electrical stimulation of the implanted ear. Throughout the period when discrimination data were being obtained, frequent checks were made of detection thresholds for the electrical stimuli to insure their stability.

Apparatus

During training and testing sessions the subjects sat in double-walled sound attenuating chambers (IAC type 1201A or Tracoustics model RE-240-B). A light-display panel was positioned in front of the subjects, a telegraph key was located within reach of either hand, and a tube for delivery of applesauce reinforcers was positioned near the mouth. For acoustic stimulation, earspeakers (Beyer Dynamic DT48 or TDH 49) fitted with circumaural cushions (Pfingst et al., 1975) were positioned against the subject's head.

Sinusoidal stimuli were generated by a Rockland frequency synthesizer, attenuated by a Wilsonics (model PATT) attenuator, gated by a custom-built tone switch and then passed to the earspeaker or to a constant-current stimulator (modified slightly from the design described by Spelman et al., 1978). For electrical stimulation, the output of the constant-current stimulator was connected directly to the implants through a percutaneous connector (Pfingst et al., 1989).

Sinusoidally amplitude-modulated noise signals were generated by using the output of the Rockland frequency synthesizer to modulate white noise (20 Hz to 20 kHz or 2 Hz to 50 kHz) signals generated by General Radio random noise generators. A multiplier, built in house, was used for this purpose. 100% modulation was used for all SAM noise experiments.

Acoustic stimuli were calibrated using a 1/4 inch microphone mounted in the ear cushion (Pfingst et al., 1975).

Experimental paradigms and data collection were controlled by LSI 11/23 and IBM PC computers.

Implants

Subject M1 had implants consisting of two spherical platinum iridium (Pt-Ir) electrodes, one placed just inside the round window and one placed in a small hole drilled in the cochlear bone near the apex.

The remaining subjects had multichannel scala tympani electrode arrays. Two of these had banded Pt-Ir electrodes surrounding a silicone rubber carrier. One of these banded arrays (for subject M2) consisted of platinum-iridium wire wound around a silicone rubber carrier to create bands 0.5 mm wide (Xue and Pfingst, 1989). In this implant only one electrode pair, spaced at 1.5 mm between the centers of the bands, was used. The other banded array (for subject M3) was manufactured by Nucleus, Ltd. (Lane Cove, Australia) and consisted of 9 platinum-iridium bands spaced 0.7 mm apart (center to center), with the most basal band located at the round window niche. Three pairs of electrodes from this implant were tested as detailed in the Results section. The remaining scala tympani implant (for subject M4) consisted of 0.2 mm diameter Pt-Ir spherical electrodes arranged on either side of a tubular silicone rubber carrier (Xue and Pfingst, 1989). There were three electrodes arranged longitudinally on each side of the carrier. For the experiments reported here, a pair of electrodes spaced 1.5 mm apart (center to center) on one side of the carrier was used. Separations of the tested electrode pairs, as well as the thresholds and dynamic ranges of these pairs, are given in Tables I and II.

TABLE I

THRESHOLDS AND DYNAMIC RANGES FOR 100 HZ ELECTRICAL SINUSOIDS FOR THE IMPLANTS AND ELECTRODE PAIRS REPRESENTED IN FIG. 3

Subject	Separation of tested pair (mm center to center)	Threshold		Dynamic range (dB)
		(dB re 1 mA rms)	(μA rms)	
M1	*	−49.4	3.39	21
M2	1.5	−53.6	2.09	23
M3	2.1	−60.2	0.98	25
M4	1.5	−59.4	1.07	30

* One electrode in the scala tympani near the round window and one in a hole in the cochlear wall near the apex.

TABLE II

THRESHOLDS AND DYNAMIC RANGES FOR 100 HZ ELECTRICAL SINUSOIDS FOR THE THREE ELECTRODE PAIRS (SUBJECT M3) REPRESENTED IN FIG. 5

Electrode pair	Separation (mm center to center)	Threshold		Dynamic range (dB)
		(dB re 1 mA rms)	(μA rms)	
C–D	0.7	−50.5	2.99	20
B–E	2.1	−60.2	0.98	25
A–F	3.5	−64.7	0.58	30

Psychophysical procedures

All psychophysical procedures used in this study have been described previously. The procedures for measuring threshold and dynamic range will be reviewed briefly here, and then procedures for measuring frequency and level difference limens will be described in more detail.

Thresholds (Pfingst et al., 1979) were measured using a go, no-go procedure. In this procedure, subjects initiated each trial by pressing a telegraph key in the presence of a trial-ready light. The key press initiated a randomly variable (1–6 s) foreperiod. Key releases during this foreperiod resulted in a penalty time out (see below) 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 signal and was unmarked on catch trials (see below). Key releases during the observation interval (i.e. within 1 s of stimulus onset) were reinforced by delivery of 0.2 cc of applesauce to a spout located near the subject's mouth. For all threshold experiments, the method of constant stimuli was used. Stimuli were selected 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. To determine thresholds, percent 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. 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 controlling 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 discrimination procedure in which frequency and level of the test stimuli were varied simultaneously with respect to the reference stimulus (Pfingst and Rush, 1987). The rationale for this procedure is discussed in the Introduction above. The basic discrimination procedure utilized a go, no-go task similar to the threshold task described above except that a reference stimulus was presented during the variable foreperiod and the subject was reinforced for releases made within 1 s after the stimulus changed (Pfingst et al., 1983). For the discrimination task, repeating stimuli (200 ms on and 100 ms off) were used. Changes in the attenuator and frequency-synthesizer settings always occurred during one of the periods when the stimulus was off, and with no change in the duration of this period.

The test-stimulus levels at which the percent responses to each frequency change were minimum were determined as follows. The test stimuli differed from the reference stimuli in frequency, level, or both frequency and level except on catch trials where the test-stimulus and reference-stimulus parameters were identical. For each test-stimulus frequency, a series of levels near the estimated equal-loudness point was used, with the step size being approximately one third to one half of the level difference limen for the parameters under study. The strategy was to present a number of test-stimulus levels for each frequency change, one level per trial, and to determine for which of the levels the minimum percent responses to the stimulus change occurred. Sample results are shown in Figs. 1 and 2. These minimum points, one for each test-stimulus frequency, were assumed to be the levels at which the discrimination was made on the basis of frequency-based cues with a minimum of assistance from level-related cues. Stability of these minimum points was checked throughout the experiment.

Results from the frequency and level discrimination experiments were used to determine the test-stimulus levels to be used in measuring the frequency difference limens. The percent responses to stimuli at these levels were measured as a function of test-stimulus frequency to form psychometric functions. The frequency difference limen was defined as the frequency change corresponding to 50% correct responses, based on these psychometric functions (see Pfingst and Rush, 1987 for further examples). Twenty trials per stimulus were used to form the psychometric functions. For the experiments reported in this paper we averaged the last six stable difference limens, except in the case of subject M3 where the experiment was terminated after collection of three stable measures due to a problem with the percutaneous connector.

Level difference limens were measured on trials where the reference-stimulus and test-stimulus frequencies were the same. The level difference limen was defined as the level change at which the subject responded to the test stimulus on 50% of the trials.

Guess rates were measured using catch trials, where both frequency and level of the reference and test stimuli were the same. We attempted to keep the guess rate constant by controlling the duration of a penalty time out as described for the detection-threshold procedures above.

Several points are worth noting regarding the characteristics of the frequency and level discrimination data for the stimuli used in this experiment. These will be described below before proceeding with a description of the results of varying the reference-stimulus level.

Fig. 1 shows data from an experiment using sinusoidal electrical stimuli. For each test-stimulus frequency, the percent responses reached a minimum at levels at or near the level of the reference stimulus but shifted to slightly higher levels as the frequency of the test stimulus increased. Tests were run at levels shifted ±1/4 dB from those shown in this figure, but no consistent drops in the percent responses below the rates illustrated here were seen.

In general, for the electrical stimuli used in these experiments, the effects of varying the test-stimulus level relative to the level of the reference stimulus were small compared to those seen when higher-frequency electrical sinusoids were used (see Pfingst and Rush, 1987). The test-stimulus levels at which the minimum percent responses occurred in the present experiments were at or near the reference-stimulus levels. The slopes of the percent responses vs. test-stimulus level functions near these minimum points were usually relatively shallow so that often the percent responses at the minimum was close to that at 0 dB re the reference-stimulus level. The difference between the level at which the minimum percent responses occurred and reference-stimulus level increased with frequency, but was never more than 2 dB. An analysis of the percent responses vs. test-stimulus level contours for cases where the minimum percent responses fell between 25% and 75%, and excluding cases where the minimum was at the reference-stimulus level, revealed that the minimum percent responses for each test-stimulus frequency differed from the percent responses at the level equal to the reference stimulus by 1% to 35% averaging 12%. The results are consistent with the flat or slightly sloping equal-loudness contours and the relatively large level difference limens typically seen for low frequency electrical sinusoids.

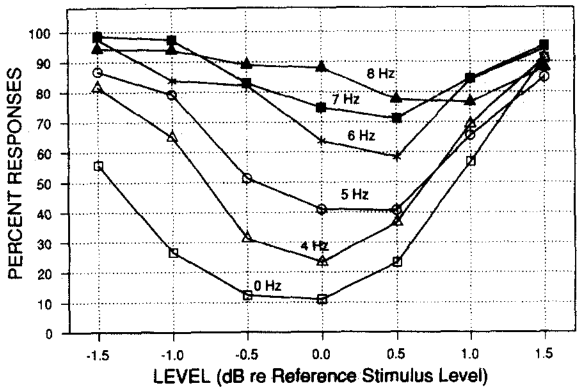

Fig. 1. Results of a frequency and level discrimination experiment using sinusoidal electrical stimulation with subject M4. The percent responses (key releases within 1 s after onset of the observation period) are plotted for each test stimulus as a function of level of the test stimulus, in dB of current relative to the reference-stimulus current. Each curve is for a different test-stimulus frequency. The labels for the curves give the difference between the test and the reference-stimulus frequencies. The reference stimulus was 100 Hz at 23 dB SL (15.1 μAmp rms). Each point is based on 100 trials.

The direction of shift of the minimum points as a function of frequency paralleled the direction of shift in detection thresholds as a function of frequency for that electrode pair. In three cases where the detection thresholds increased as a function of frequency, an increase was seen in the level at which the minimum point in the percent responses vs. test-stimulus level contour occurred as test-stimulus-frequency increased (as in Fig. 1). In one case (M4) where the detection thresholds decreased from 100 Hz to 175 Hz, a decrease in the levels of the minimum points was seen as frequency increased. In previous experiments, we found that when the test-stimulus frequency was lower than the reference, the levels where the minimum points were obtained changed as a function of frequency change in the direction opposite that observed when frequency of the test stimulus was higher than the reference. In this experiment we used only test-stimulus frequencies higher than the reference stimulus.

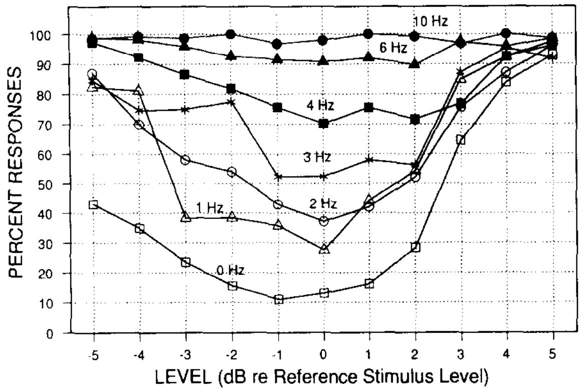

Fig. 2. Results of a frequency and level discrimination experiment using acoustic SAM noise stimulation with subject M3. The percent responses (key releases within 1 s after onset of the observation period) are plotted as a function of level of the test stimulus, in dB relative to the reference-stimulus level, for each of 7 test-stimulus frequencies ranging from 0 Hz to 10 Hz above the reference-stimulus frequency. The reference stimulus was 100 Hz at 40 dB SL. Each point is based on 100 trials.

With acoustic SAM noise stimuli, the detection thresholds did not change as a function of modulation frequency and the minimum points in the frequency and level discrimination functions for each test-stimulus frequency were at the reference-stimulus level in 87% of the cases (e.g. Fig. 2). In cases where the level at the minimum point differed from the reference-stimulus level, as for example in the 0 Hz contour in Fig. 2, the percent responses at this point always differed by less than 10% from that at the reference-stimulus level.

Results

Effects of reference-stimulus level

Frequency difference limens for electrical stimulation for the four subjects are plotted as a function of the sensation level of the reference stimulus in Fig. 3. The levels tested ranged from the lowest level at which we could obtain reliable difference limens to near 80% of the dynamic range. Subject M2 was also tested at a higher level in the dynamic range (87%) because we observed during initial testing that the difference limens at this level were markedly lower than those seen just 2 dB lower at 78% of the dynamic range. In all subjects, we attempted to measure frequency difference limens at levels 2 dB below the lowest levels shown in Fig. 3, but we found the difference limens at these levels to be very large and unreliable, so studies at these levels were discontinued.

Frequency difference limens for 100 Hz electrical stimuli decreased as a function of level through all or most of the tested range. However, the rate of decrease varied as a function of level in different ways for each subject. For subject M4 the greatest slopes in the frequency difference limen vs. level functions were in the lower half of the tested range, whereas for subject M2, the difference limens decreased most as a function of level at the highest level tested. The remaining two subjects fell between these extremes.

Detection thresholds and dynamic ranges for these four implants at 100 Hz for the electrode pairs represented in Fig. 3 are given in Table 1. The data in Fig. 3 are plotted as a function of sensation level (dB above threshold). This metric for the abscissa was chosen somewhat arbitrarily and a number of other choices are possible. For example, if the curves in Fig. 3 were plotted as a function of threshold current in decibels, rather than in sensation level, the curves for subjects M1 and M2 would be shifted to the right by about 6 and 10 dB respectively in relation to the curves for subjects M3 and M4.

A two-way analysis of variance comparing the lowest, middle and highest levels of stimulation for each subject was performed using a fixed-effects model. For subject M2 we used 18 dB SL as

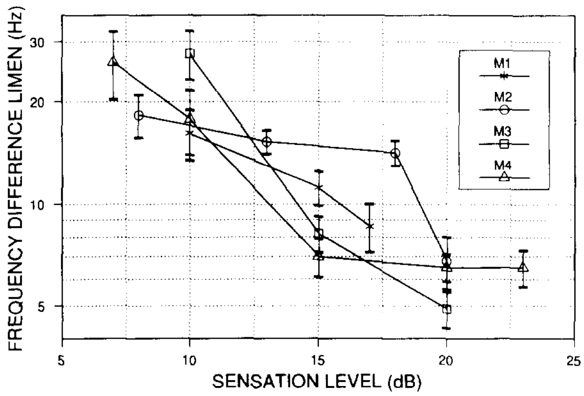

Fig. 3. Frequency difference limens for 100 Hz electrical sinusoidal reference stimuli plotted as a function of sensation level of the reference stimulus for four subjects. Means and 2 SD (i.e. ±1 SD are shown.

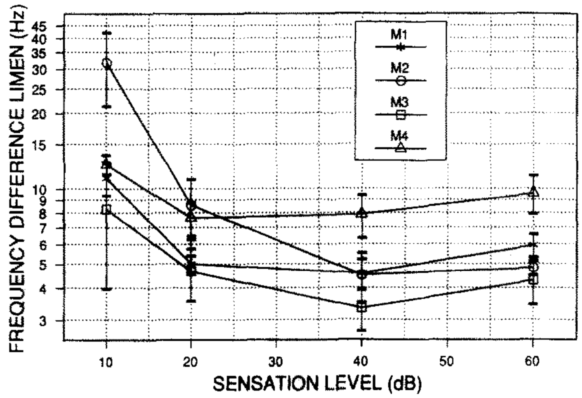

Fig. 4. Frequency difference limens for 100 Hz acoustic SAM noise reference stimuli plotted as a function of sensation level of the reference stimulus for four subjects. Means and 2 SD are shown.

the highest level because 20 dB SL was relatively higher in the dynamic range of the implant (87% of the dynamic range) than the highest levels for the other subjects. A significant level effect ($F_{2,51} = 129$; $P < 0.001$) and a significant subject-level interaction ($F_{6,51} = 16.85$; $P < 0.001$) were found *.

Frequency difference limens for the modulation frequency of acoustic SAM noise stimuli for these same subjects are plotted as a function of sensation level in Fig. 4. Although there were significant differences between the subjects in the magnitudes of the frequency difference limens and in the shapes of the curves near the detection threshold, the curves were similar in that in all cases the slopes decreased with increasing level above threshold and then increased slightly at the highest levels tested. Detection thresholds for these stimuli for the four subjects were all within 3 dB of each other (11 to 14dB SPL).

A two-way analysis of variance using a mixed model with one random factor (subjects) and a fixed factor (level) showed a significant level effect ($F_{3,80} = 54.8$; $P < 0.001$) and a significant subject-level interaction ($F_{9,80} = 15.7$; $P < 0.001$).

Several differences are apparent between the frequency discrimination data for sinusoidal electrical stimulation and those for acoustic SAM noise stimulation of the contralateral ears in the same subjects (Fig. 3 vs. Fig. 4). First, the effects of level for the electrical stimuli were different than those seen for the acoustic stimuli. For the electrical sinusoidal stimuli the difference limens decreased throughout the range tested whereas for the acoustic SAM noise stimuli the difference limens dropped within the first 20 dB above the detection threshold and then showed little further decrease, or even an increase, at higher levels. Subject M4 showed the most saturation in the frequency difference limen vs. level functions for electrical stimuli. However, this occurred only at relatively high levels in the dynamic range, somewhere between the upper half and the upper two thirds of the dynamic range. For the acoustic stimuli this subject's frequency difference limens decreased, for the most part, only up to 20 dB SL or 23% of the dynamic range ** and then tended to asymptote at higher levels. Second, note that with acoustic SAM noise stimuli we were able to obtain reliable frequency difference limens at 10 dB SL or 11% of an 88 dB dynamic range whereas with electrical stimuli we were able to obtain reliable results only as low as levels representing 23% to 50% of the dynamic range.

At the highest levels tested, the frequency difference limens for the electrical sinusoids and the acoustic SAM noise signals fell in roughly the same range: 5 to 7 Hz for the electrical stimuli (Fig. 3) and 4 to 10 Hz for the acoustic (Fig. 4). A comparison of frequency difference limens for electrical stimuli with those for acoustic stimuli for the four subjects at the highest levels tested showed differences (absolute values) of 2.7, 2.0, 0.6, and 3.1 Hz, averaging 2.1 Hz. An analysis of variance (fixed-effects model) showed no significant difference in the frequency difference limens for the two waveforms at these levels ($F_{1,37} = 2.63$; $P > 0.05$).

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[*] The level effect was, of course, even stronger if the 20 dB SL level for subject M2 was used as the highest level with either 13 dB SL or 18 dB SL as the middle level. Under these conditions the subject-level interaction terms were slightly smaller, but still significant.

[**] The percent of dynamic range calculations for the acoustic stimuli are based on an 88 dB dynamic range, equivalent (based on the reaction-time measures), to the loudness range used for electrical stimulation.

There was no obvious relationship between the relative magnitude of the difference limens for the electrical as compared to the acoustic stimuli within subjects. Thus subject M2, which had the highest difference limens for electrical stimuli at the higher levels of stimulation, ranked in the middle of the four subjects for acoustic difference limens at these levels. Subject M4, which had the highest acoustic difference limens at the higher levels, ranked relatively low with regard to electrical difference limens.

Effects of electrode separation

Frequency difference limens are plotted as a function of sensation level for three concentric electrode pairs in Fig. 5. The implant is illustrated in the inset. The closest pair of electrodes tested was pair C–D. The intermediate pair, B–E, bracketed C–D and the widest pair, A–F, bracketed B–E. The thresholds and dynamic ranges for these pairs are given in Table II.

At a given sensation level, the frequency difference limens decreased as a function of electrode separation. The difference limens for the most closely spaced pair were higher than those for the more widely spaced pairs at both sensation levels tested. Since the most closely spaced pair had the highest threshold and the smallest dynamic range, the frequency difference limens for that pair would be even higher than those of the more widely spaced pairs at comparable levels if the data were plotted using either threshold current or percent of dynamic range on the abscissa. A two-way analysis of variance (fixed effects model) comparing the two levels at which all three pairs were tested showed a significant electrode effect ($F_{2,12} = 4.2$; $P < 0.05$) and a significant level effect ($F_{1,12} = 39.5$; $P < 0.001$). A comparison of the two more widely spaced pairs (A–F and B–E) across level showed a significant level effect ($F_{2,12} = 37.5$; $P < 0.001$) but not a significant difference between the two pairs ($F_{1,12} = 1.2$; $P > 0.05$).

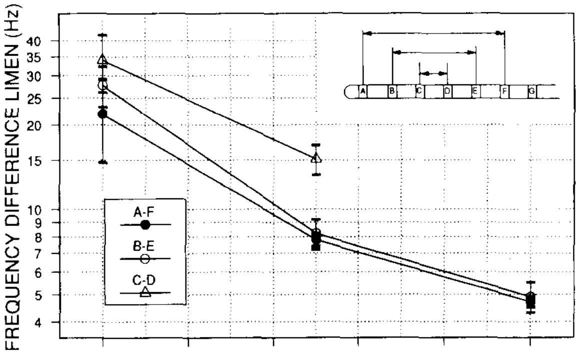

Fig. 5. Frequency difference limens for 100 Hz electrical sinusoidal reference stimuli plotted as a function of sensation level of the reference stimulus for three electrode pairs in subject M3. Means and 2 SD are shown. The implant is depicted in the inset.

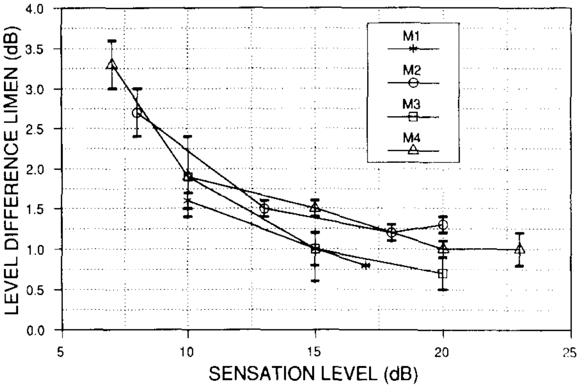

Fig 6. Level difference limens for sinusoidal electrical stimuli plotted as a function of sensation level of the reference stimulus for the four subjects using the same electrode pairs represented in Fig. 3. The reference stimulus was 100 Hz and the test stimuli were higher in level than the reference (except on catch trials). Means and 2 SD are shown.

Comparison of frequency difference limens with level difference limens

Level difference limens, for increases in level, for the four subjects and electrode pairs shown in Fig. 3 are plotted as a function of sensation level of the reference stimulus in Fig. 6. For all four subjects the level difference limens decreased as a function of level in a similar fashion. Thus the between-subjects differences in slopes seen in the frequency difference limen vs. level data (Fig. 3) were not seen in the level difference limen vs. level data. A two-way (fixed effects) analysis of variance was run using the highest, middle and lowest levels tested but omitting the 20 dB SL level for subject M2 as with the frequency discrimination data for electrical sinusoids from Fig. 3. In this case there was a significant subject effect ($F_{3,51}$ = 48.2; $P < 0.001$) as well as a significant level effect ($F_{2,51}$ = 191; $P < 0.001$) and a significant level-subject interaction ($F_{6,51}$ = 11.7; $P < 0.001$). The analysis was extended to a mixed model with one random factor (subjects) and one fixed factor (level), to allow us to make inferences about the effects of subjects in a larger population. This required ignoring the slight within-cell imbalance in sample size due to our having only three measures per level for subject M3. Under these assumptions we did not find a significant subject effect ($F_{3,6}$ = 4.4; $P > 0.05$).

Discussion

The principle findings of this study were:

1. Frequency difference limens for electrical stimulation were large in the lowest third of the dynamic range and decreased as a function of level through most of the dynamic range, while those for the acoustic stimuli were lowest at 20 to 40 dB above the detection threshold and then increased slightly.
2. For the electrical stimuli, the slopes and relative positions of the frequency difference limen vs. level functions varied from subject to subject, and with changes in electrode configuration within a subject, and were related to threshold level and dynamic range.
3. At higher levels of stimulation, frequency difference limens for sinusoidal electrical stimulation of the more widely spaced electrodes (≥ 1.5 mm) were similar in magnitude to those for acoustic SAM noise stimulation of the normal ear.
4. The slopes and relative positions of level difference limen vs. level functions for electrical stimuli did not parallel those of the frequency difference limen vs. level functions collected simultaneously from the same ears.

One of the most interesting findings of this study, and perhaps one of the most instructive with regard to cochlear prosthesis processor design, was the observation that frequency difference limens were strongly dependent on the reference-stimulus level over a large part of the dynamic range of the implant. This finding contrasts with the finding that frequency difference limens for acoustic SAM noise stimulation of the normal-hearing ear in these same subjects reached a minimum within about 20 dB to 40 dB above the detection threshold. The shape of the acoustic functions was expected, given the finding by Viemeister (1979) that temporal modulation transfer functions for SAM noise in subjects with normal hearing were affected by level only near threshold.

The fact that frequency difference limens for electrical stimulation of the four subjects were affected by level in ways that were not paralleled in the data for acoustic stimuli suggests that the intersubject differences were due to differences in the implants or the condition of the ears of these subjects rather than to more general differences in ability to perform a frequency discrimination task. The thresholds and dynamic ranges of the implants suggest differences in the number of nerve fibers stimulated in each of the four subjects. In previous studies we found correlations between thresholds and dynamic ranges and the number of nerve fibers remaining in the stimulated ears. Subjects with relatively high thresholds and small dynamic ranges tended to have poorer nerve survival (Pfingst and Sutton, 1983, 1984; Pfingst et al., 1985). Thus the threshold and dynamic range data for subjects M1 and M2 would suggest poorer nerve survival in these cases. A reduction in nerve fibers might be expected to give larger frequency difference limens at comparable levels because fewer fibers would be available to carry the temporal information. The data in Fig. 3 are consistent with this hypothesis. Also consistent with this hypothesis are recent observations by Tong et al. (1989) who found that, in human subjects with multichannel electrodes, pulse rate difference limens for electrode pairs with smaller dynamic ranges were larger than those for electrode pairs with larger dynamic ranges.

Bacon and Viemeister (1985) found that temporal modulation transfer functions for subjects with damaged ears were affected by level, with sensitivity to modulation decreasing at lower levels. They present evidence linking this effect to the effective narrowing of the hearing-impaired subjects' 'internal' bandwidths. One effect of this narrowing of bandwidth would be a reduction on the number of nerve fibers carrying the signal, but other mechanisms could also account for the reduction in sensitivity to modulation observed in their experiments.

The effects of electrode spacing on electrical frequency difference limens may also be related to the number of nerve fibers stimulated. At a fixed current level, we would expect more nerve fibers to be stimulated by a more widely spaced pair of electrodes than by a more narrowly spaced pair. However, the current level at the excitable elements may also be affected by electrode separation, which complicates the interpretation of the effect of electrode spacing. Thus, the decrease in frequency difference limens with increasing electrode separation is consistent with, but does not prove, the hypothesis that the number of nerve fibers synchronized affects the difference limen.

With electrical stimuli, we were unable to obtain any reliable frequency difference limens at levels below 7 to 10 dB SL. Given the small dynamic ranges for electrical stimulation, 10 dB SL at 100 Hz represents about one third to one half of the dynamic range. However, there is some evidence that loudness growth for low frequency electrical stimuli is slower at low levels than at high (see Pfingst, 1984), so the loudness of the stimulus at 10 dB SL may not have been one third to one half of the loudness at the upper limit of the dynamic range. The high difference limens for electrical stimuli at 7 to 10 dB SL and the apparent inability of our subjects to discriminate frequency changes at lower levels was unexpected, given that the temporal encoding of stimulus frequency in auditory nerve fibers seems to occur at levels at or below the rate thresholds of the fibers (Hartmann et al., 1984). At least two explanations of this discrepancy may be offered. It may be that the rate thresholds for most single auditory nerve fibers occur at levels significantly above the behavioral detection thresholds. Comparison of behavioral and neural thresholds across species, while not conclusive, lends support to this hypothesis (Pfingst, 1988). A second possibility is that synchronized responses in a large population of auditory nerve fibers is necessary for discrimination of a frequency change. Since the thresholds of auditory nerve fibers for either synchrony or rate are distributed over a range almost as large as the dynamic range of hearing for electrical stimuli (Glass, 1983; Hartmann et al., 1984; van den Honert and Stypulkowski, 1984), only a few fibers may show synchronized responses near threshold. This latter hypothesis is also consistent with the observation that the perception of pitch in acoustic SAM noise signals is weak or absent at near-threshold levels.

As stimulus level is increased above threshold, two types of changes occur in the auditory nerve: 1) the synchrony of the discharges of individual nerve fibers, as reflected in the synchronization index, increases rapidly to saturation within a few dB of the fiber's threshold, and 2) the number of fibers responding to the stimulus with synchronized discharges increases. Either or both of these events could contribute to the decrease in psychophysical frequency difference limens as a function of level. However, the continued decrease in the difference limens with increases in level to near the upper limit of the dynamic range, suggests that the number of nerve fibers activated is important, since the fibers activated near threshold are synchrony saturated within a few dB of threshold and thus could not contribute to the increased discrimination performance by further increases in synchrony. This line of reasoning suggests that the number of nerve fibers remaining in the implanted ear should be a variable influencing frequency discrimination ability. The data on acoustic SAM noise stimulation of normal-hearing ears, which presumably have close to a full complement of auditory nerve fibers, suggest that it is possible to reach functional synchrony saturation once a sufficient number of fibers are synchronously activated. However the condition of the population of auditory nerve fibers at 20 dB to 40 dB above threshold, where the psychophysical data reach a minimum, must be better defined physiologically in order to test this hypothesis.

The fact that the difference limens for sinusoidal electrical and SAM noise acoustic stimuli were similar at the highest levels tested is somewhat encouraging for the notion that both types of signals are dependent on the same fundamental processes, e.g. frequency following by a population of auditory neurons. Although there were striking differences in the effects of level on the discrimination of these two types of stimuli, these could be a function of differences in the conditions of the stimulated ears rather than a function of the signals themselves. Thus, acoustic amplitude-modulated noise may be a good model for studies of nonspectral pitch relevant to auditory prostheses at high levels of stimulation. However, at lower levels the data obtained using this signal in subjects with normal auditory nerves may not be applicable to subjects with damaged nerves, which includes almost all candidates for auditory prostheses. Further experiments, in which the two types of stimuli are tested under more comparable conditions, are needed.

We have shown previously that level difference limens decrease as a function of reference-stimulus level (Pfingst et al., 1983). The fact that these limens decreased as a function of level in a similar fashion across the four subjects in this study lends credence to the notion (discussed above) that the differences seen in the slopes of the frequency difference limen vs. level functions across subjects are attributable to the differences in the ears of the subjects, not to more general differences in discrimination performance. These data also suggest that the differences in the frequency difference limen vs. level functions across subjects were not due to differences in detection of level changes in the signals, at least in so far as these were reflected in discrimination of level changes using long-duration (200 ms) stimuli. However, more rapid changes in level might involve different mechanisms (Smith and Brachman, 1980). Previously we have shown data on a few subjects indicating that those with poorer nerve survival had lower frequency difference limens than those with moderately good nerve survival (Pfingst and Sutton, 1983; Pfingst et al., 1983). On the basis of their threshold and dynamic range data, we suggest that subjects M1 and M2 might have poorer nerve survival than subjects M3 and M4. The lower level difference limens of subject M1, which had the highest thresholds and smallest dynamic ranges, are consistent with this picture, but the data for subject M2 are not.

Auditory prostheses rely heavily on temporal cues for frequency encoding. In single channel cochlear prostheses, temporal cues provide the only information about stimulus frequency. In multichannel devices both temporal and place cues are used. These two cues can be treated separately as in the Cochlear Corporation (Nucleus Ltd.) multichannel device where temporal cues are used to convey low frequencies such as voice fundamental frequency and place cues are used to convey higher frequencies representing first and second formants in speech signals (Clark, 1986). In multichannel analog devices such as the Symbion device (Eddington, 1980; Parkin and Stewart, 1988), where the outputs of different band-pass filters are sent to different electrodes, temporal and place cues are coordinated in that higher frequency outputs are sent to more apically located electrodes. However, since the number of channels in these devices is typically small (e.g. 4), small changes in signal frequency are often encoded only by frequency changes within a single channel. If a temporally coded signal in any of these devices drops into the lower half to lower third of the dynamic range, the frequency information in those signals may be undiscriminable by the subject. The data presented here, then, suggest that for patients with compromised auditory nerves, it may be beneficial to discrimination performance to compress signals into the upper two thirds to one half of the dynamic range of the implant.

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