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SECTION 12. PSYCHOPHYSICS

PITCH MATCHING OF ELECTRIC AND ACOUSTIC STIMULI

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INTRODUCTION

In the electric coding of speech for multiple-electrode cochlear implants, acoustic frequency ranges are mapped onto electrodes. The question arises as to whether the pitches of the electrically evoked hearing sensations are similar to those evoked by the corresponding acoustic stimuli in normal-hearing listeners. Obviously, the sensations are similar enough for many postlingually deaf implant users to understand speech with a minimum of retraining, but it is unlikely that the electric signals sound identical to the acoustic ones. There will also be differences between implant users arising from the variable insertion depth of the electrode array, the number of electrodes in use, and the frequency-to-electrode mapping. The most direct method of determining pitch is to ask implant users to compare electric and acoustic stimuli, but studies of this sort have been hampered by the fact that very few implant users have usable hearing for acoustic signals. In 1978, Eddington et al¹ reported pitch-matching results for one unilaterally deaf volunteer. They concluded that pitch matching was "roughly consistent with electrode position and tonotopic maps of the cochlea derived from basilar membrane motion and hearing loss measurements." Several other studies²⁻⁶ have investigated the relative pitch of electric signals using identification, scaling, and discrimination paradigms. These studies have established that electrode placement, electrode configuration, and rate of stimulation all affect the perceived pitch, and that the pitch increases tonotopically from apical to basal electrode positions. They have not determined the pitch of electric stimuli in an absolute fashion that can be compared with acoustic stimuli, however. A knowledge of the absolute pitch of electric stimuli for individuals, or as a function of position in the cochlea, would be very useful in optimizing the frequency mapping for cochlear implants.

The present study directly compared the pitch of acoustic pure tones in one ear with electric signals in the other ear of implant users with some residual hearing in the nonimplanted ear. The main questions addressed were whether the pulse rate of a matched electric stimulus would be equal to the frequency of the acoustic tone, and whether the electrode used in the matched stimulus would correspond in position to the place of maximum basilar membrane motion produced by the acoustic tone in a normal cochlea.

METHOD

The subjects were postlingually deaf adults with some residual hearing in the nonimplanted ear. Average audiometric thresholds at octave frequencies from 250 Hz to 4 kHz

were 80 (10), 96 (12), 102 (11), 102 (11), and 98 (6) dB hearing level, respectively. The numbers of subjects with measurable thresholds at each frequency are shown in parentheses. All subjects were implanted with the 22-electrode cochlear implant.⁷ All subjects were regular cochlear implant or hearing aid users and the majority wore both devices most of the time.

Acoustic and electric stimuli were produced by computer control of a "bimodal" aid that combined a cochlear implant speech processor and a hearing aid processor. The electric signals were biphasic pulse trains with a duration of 500 milliseconds (ms) at a fixed rate on a bipolar electrode pair. The acoustic stimuli were pure tones of 500-ms duration. The tones were presented via an Oticon AN1000 hearing aid receiver and ear mold at levels that were comfortable for the listener. The levels varied between subjects and between frequencies because of differences in thresholds and dynamic ranges. Before starting a block of pitch comparisons, the intensity of each electric stimulus was adjusted to match the loudness of the acoustic stimulus.

Electric and acoustic stimuli were presented in pairs. The subject was asked which stimulus was higher, and the judgments were repeated in different sessions and within sessions to test their reliability. The subject listened to the alternating signals for as long as was necessary to make a decision (usually about three alternations). There was sometimes a broad range in which the subject seemed uncertain which stimulus was higher. To cope with this situation, the subject was allowed to choose from three responses: "acoustic higher," "electric higher," or "both the same."

In the first experiment, a set of pure tone frequencies was chosen for each subject that spanned the frequency range of usable hearing in octave or half-octave steps. Within a block of trials, the frequency of the acoustic stimulus was kept fixed, the pulse rate of the electric signal was kept fixed, and the position of the stimulated electrode was varied. The second experiment was similar to the first one, except that all stimuli within a block of trials were presented to the same electrode and the electric pulse rate was varied. The rate was varied from 50 to 1,000 pulses per second (pps) in steps of 25 pps, but not every pulse rate was tested if a consistent pattern of responses emerged.

To provide reliable electrode position information, the subjects were asked to undergo an x-ray study using a modified Stenver's view, with the intracochlear portion of the electrode array in the plane of the film.⁸ Angular positions for electrodes were measured about the center of the cochlear

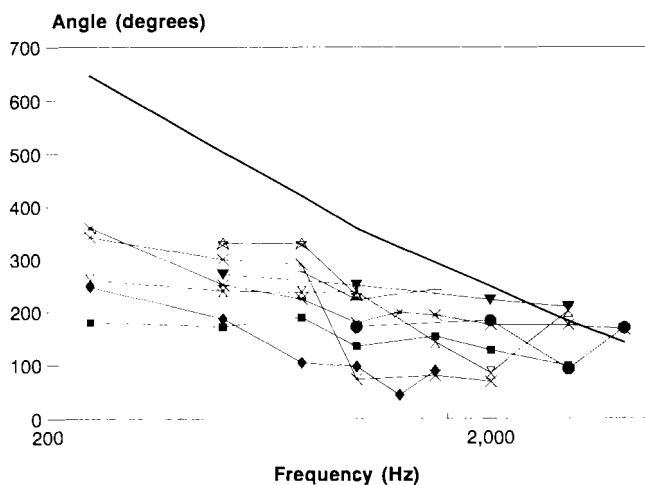


Fig 1. Frequency versus position in cochlea from pitch-matching experiment with 9 cochlear implant users compared to normal listeners (diagonal bold line). Pulse rate was 250 pps. Different symbols indicate different subjects.

spiral, with the hook region of the basilar membrane at 0° . Angular positions were used because the position of the electrode array within the scala tympani is probably close to the outer wall of the cochlear spiral, so that distances along the array do not correspond directly to distances along the basilar membrane. Angular positions eliminate this discrepancy. The angles of the most apical electrodes for the subjects varied from 201° to 451° . Bredberg⁹ provides anatomic data from humans that indicate the relationship between angles and proportional distances along the organ of Corti. These proportions were used in conjunction with the formula of Greenwood¹⁰ to calculate characteristic frequencies corresponding to angular positions in the cochleas of normal-hearing listeners.

RESULTS

Figure 1 shows the results for 9 subjects from the experiment in which electric pulse rate was held constant at 250 pps and electrode position was varied. The symbols represent the electrode positions at which responses changed from "electric higher" to "acoustic higher" as the electrode was shifted in a basal to apical direction in the cochlea. These "best matching positions" were determined from a least-squares fit to the responses for each acoustic frequency. The bold line in Fig 1 shows frequency coordinates on the basilar membrane derived from other studies.^{9,10} At the apical end of the array, the pitch matches are two to three octaves lower than the frequencies for the same angular position in normal ears. At the basal end, the difference is much less.

Figure 2 shows the results for 8 subjects of pitch matching when electric pulse rate was varied on the most apical electrode. Although 12 subjects participated in total, only 5 occur in both Figs 1 and 2. In Fig 2, there was a spread of results across subject, with a tendency for the "matched" pulse rate to exceed the acoustic frequency at the lowest frequency tested (62 Hz). At higher frequencies, the matched rate was within one octave of the pure tone for most subjects. Temporal coding of pitch in terms of electric pulse rate seems to be quite imprecise, but does not involve a shift like the place

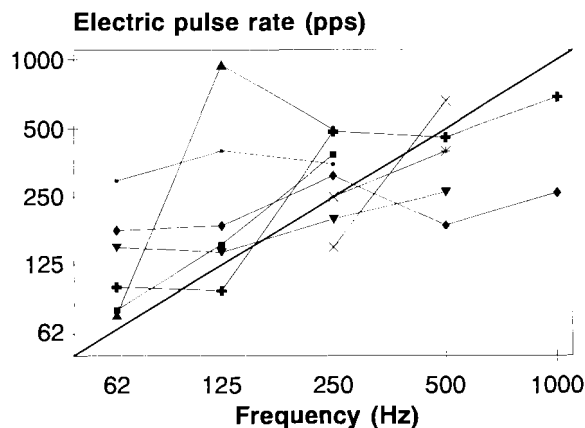


Fig 2. Frequency versus electric pulse rate derived from pitch-matching experiment with 8 implant users (symbols). Most apical electrode was used. Solid line indicates equality of pulse rate and frequency.

coding in terms of electrode position.

DISCUSSION

In a small number of cases, the subjects reported that the electric and acoustic stimuli sounded identical, but this was generally not the case. Many of the subjects found the pitch comparisons difficult to do, and this also indicates that the electric and acoustic sounds differed in timbral qualities such as roughness, fullness, etc., as well as pitch. It is also possible that electric stimuli evoke sensations that are more like tone complexes or noises than pure tones, so that they may have had more than one pitch component. Despite the difficulty of the task, most of the responses followed the expected pattern of increasing pitch with more basal electrode and/or increasing pulse rate. This is consistent with previous psychophysical investigations of pitch.¹⁻⁶

The bold line in Fig 1 represents the angular positions of points on the basilar membrane where maximum excitation occurs in response to pure tone frequencies in a normal-hearing ear.^{9,10} The experimental points for low frequencies are displaced well to the left of the line. In other words, the pitch percept evoked by electric stimulation with an electrode at a given position in the cochlea may correspond to a tone up to three octaves lower than the tone that would normally be perceived at that position. At higher frequencies, the best match points were close to the line. The trends for individual subjects and the overall trends of the data indicate a downward slope from left to right, but the slopes are smaller than for the normal-hearing function. This means that the perceived pitch varies more rapidly with position for electric stimulation than for acoustic stimulation. Regression analysis indicated a slope of -88° per octave for the complete set of data in Fig 1. For comparison, the slope of the normal-hearing line in the region shown is -109° per octave.

There are several factors that may lower the "matched" pitch of electric stimulation in the present experiment. The first is the actual site of excitation of the nerves. It is known that there are few surviving dendrites, and that the site of excitation is in Rosenthal's canal. It is known that the den-

drites do not travel radially outward from Rosenthal's canal, and that the ganglion cells in the modiolus extend around 1.75 turns, compared to 2.75 turns for the organ of Corti.⁹ To a first approximation, one would expect a variation of -69° per octave (ie, -109° per octave $\times 1.75/2.75$) in the ganglion cells. The observed angle of -88° per octave was thus intermediate between this value for excitation in the modiolus and the value of -109° per octave for excitation in the organ of Corti. Another factor is the effect of hearing impairment in the nonimplanted ear. It is known that the loss of outer hair cells will shift the point of maximum excitation on the basilar membrane in a basal direction, by an amount corresponding to half an octave.¹¹

Although this effect may contribute, it is not large enough to account for the shift of three octaves at low frequencies, nor does it account for the altered slope of the frequency-to-place relationship. A third factor may be the effect of the possible low-pitched component corresponding to the pulse rate of 250 pps in the electric stimulus. The effect of this component on the pitch comparisons is difficult to predict, although previous research suggests that "rate pitch" and "place pitch" are perceived as independent properties by implant users.² In this case, the constant rate pitch component might be expected to have little effect on the results of a matching experiment in which only electrode place was varied. Finally, one should consider the effect of learning or plasticity. It is possible that the subjects became accustomed to the sounds produced by the implant to such an extent that the matching of psychophysical stimuli was influenced by their daily experience. If this process was complete, the acoustic frequency matched to each electrode would correspond to the frequency that was usually mapped onto that electrode. This did not seem to be the case for most of the subjects.

In the second experiment, the average pulse rate of the matched electric stimulus was approximately equal to the frequency of the pure tone. Some subjects showed large deviations from the mean, however. Some of the deviations may reflect the relatively poor frequency tuning that is to be expected in severely to profoundly hearing-impaired nonimplanted ears,¹² and the poor rate discrimination in the implanted ear.⁴ In particular, some subjects are quite insensitive to rate changes, especially for pulse rates above 300 pps. A second factor that may have affected the results is the "place pitch" component arising from the fixed electrode position. It is difficult to predict the effect that this component would have on the pitch matches, and it is likely to vary across subjects because of the different depths of insertion of the most apical electrode.

IMPLICATIONS FOR FREQUENCY MAPPING

In the implant speech processor, frequency bands are "mapped" to particular electrodes, and the fundamental frequency of the voice, F_0 , is represented by the pulse rate or amplitude modulation within frequency bands. It has been assumed¹ that the pitch of an electric stimulus would approximate the pitch of a pure tone that produces a maximum of excitation on the basilar membrane at the corresponding position in a normal-hearing listener as shown in Fig 1.

Because the electrode array cannot be inserted into the full length of the cochlear spiral, the mapping of frequencies from 300 Hz to 6 kHz onto electrodes in the basal turn of the cochlea (0° to 360° in Fig 1) would have implied a considerable upward pitch shift. The results of Fig 1 imply that the perceived pitch range for many implant users is actually quite close to the normal range covered by speech stimuli. Subjects with a relatively shallow electrode insertion will still experience an upward pitch shift, but usually less than an octave. The size of this perceptual shift would be similar to the difference between adult and child voices, and thus within the normal range of variability experienced by normal-hearing listeners. This result helps to explain why most postlingually deaf adults can recognize speech at reasonably high levels of accuracy within a short time of the implant operation, and why relatively small adjustments in frequency mapping can improve speech recognition in some implant users.¹³

On the other hand, the pulse rate seems to evoke a pitch percept that is close to normal for most implant users, so there is no need to transpose frequencies such as F_0 if they are to be represented as pulse rates.

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