THE PERCEPTION OF PITCH BY USERS OF COCHLEAR IMPLANTS: POSSIBLE SIGNIFICANCE FOR RATE AND PLACE THEORIES OF PITCH

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ABSTRACT This study used subjects who had lost their hearing after acquiring language and who used cochlear implants. Trains of electrical pulses with different rates were sent to electrodes in different positions along the cochlea. Subjects reported perceived pitch using an arbitrary scale which was later normalised among subjects. At low rates of stimulation, the reported pitch depended on both electrode position and stimulation rate. Perceived pitch increased approximately logarithmically with rate, but decreased with the distance of the stimulation area from the cochlear windows. At high rates of stimulation, perceived pitch also decreased with distance from the windows, but had little dependence on stimulation rate.

1. INTRODUCTION

For more than 150 years, scientists have debated the way in which the ear encodes pitch. The debate concerns the relative importance of the rate of stimulation, and the place in the inner ear where that stimulation occurs. The basilar membrane of the inner ear has mechanical properties which vary with position in such a way that high frequency vibrations cause maximal motion at the window end and low frequencies cause maximal motion at the apical end [1]. It is therefore difficult to separate the effects of rate and position of stimulation on the perception of pitch in the normal ear because these parameters are inevitably correlated. Cochlear implants (CIs) include a linear array of electrodes which lie near to the basilar membrane (Fig 1). This allows the position and rate of electrical stimulation to be varied almost independently. In this study, CI users who had lost their hearing after acquiring language used pitch scaling to report the perceived pitch produced by series of electrical pulses with a range of rates and electrode positions.

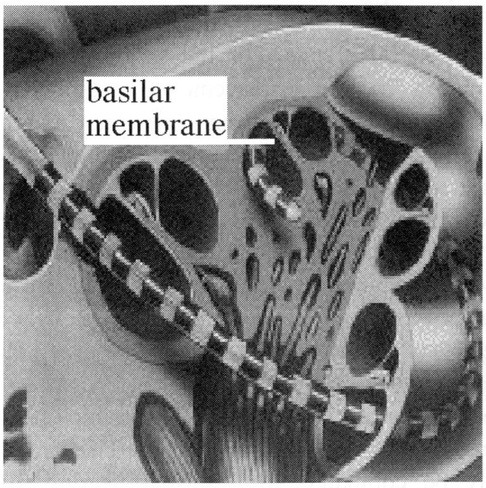

Figure 1. A schematic cut-away diagram of the implanted cochlea. The electrode array enters near the window at left and follows the first 1.5 turns towards the apical end (top right). The basilar membrane separates the two chambers of the cochlea.

The cochlea of the normal inner ear transforms an input mechanical vibration (essentially a filtered version of the acoustic signal input to the ear) to action potentials in the fibres of the auditory nerve. The cochlea is a rigid, coiled tube, divided mechanically into two along its length by the basilar membrane. The small bones of the middle ear input a displacement signal to one side of the tube via a window. This signal drives a transverse wave in the basilar membrane, whose cutoff frequency decreases along its length. As a result, high frequencies cause maximum vibration at the window end, and low frequencies cause maximum vibration at the other. In the normal ear, action potentials are produced in an array of hair cells which reside on the basilar membrane. Ohm [2] and Helmholtz [3] proposed that pitch was encoded tonotopically, i.e. by the place along the basilar membrane of the nerve stimulated (place theory). Seebeck [4] argued that nerve pulses were produced by each vibration and that their rate determined the perceived pitch (rate theory). Using place theory, it is difficult to explain the observed fine resolution of frequency (~0.2%). On the other hand, the rate theory cannot readily explain the perception of tones with frequencies many times greater than the maximum firing rate of neurones. Despite many elegant acoustic experiments, the relative importance of rate and place are still debated because, in the normal ear, the rate of mechanical stimulation of the basilar membrane is strongly correlated with position. Cochlear implants allow the local electrical stimulation of different regions of the cochlea at different rates. A range of experiments have studied pitch using CIs: Simmons et al [5] reported pitch estimates from a single subject with low resolution in position. Pitch as a function of stimulation rate was reported by Pijl [6] and by Collins et al [7].

Our study extends the work by these researchers and uses the method of pitch scaling [7,8] which has the advantages that it does not require matching of percepts that may differ in several different perceptual parameters, and that it can readily be understood and used by subjects with little knowledge of music. We studied six volunteers with implants which allowed fine resolution in both rate and place, and we present perceived pitch as a function of rate and place of stimulation. The results show remarkable consistency, given the subjective nature of the test.

2 METHOD

Six adults volunteered for this study, which is part of a project to improve the performance of CIs in delivering perception and appreciation of music. Their ages ranged from 35 to 72, and they had lost their hearing at ages between 5 and 45 years. All subjects normally use NucleusTM CI22M implants and either SPECTRA-22TM or SPrintTM processors programmed with the SPEAKTM coding strategy (Cochlear Ltd.). All subjects normally use biphasic pulses applied between pairs of electrodes separated by one temporarily inactive electrode; that stimulation mode was used in this study.

The stimuli were 1.00 s pulse trains of biphasic rectangular pulses: a 100 μs pulse, a 25 μs gap then a 100 μs pulse of equal magnitude but opposite polarity. The stimuli were loudness balanced. Each subject was asked first to increase the control of the current level to achieve a level judged to be "medium-loud", then to compare all stimuli in turn with the middle rate, middle position stimulus until the subject was satisfied with loudness equivalence.

Seven examples of each stimulus were delivered and evaluated. Presentation order was random and a training block was presented before data collection. Pitch was reported using the pitch scaling method [7,8]. Values on arbitrary scale from 0 (very low pitch) to 100 (very high pitch) were assigned by the subject to each stimulus. The values were then normalised: for each subject in each of two measurement sessions, the responses were scaled as a percentage of the total range used by the subject in that session. Electrode number was converted into position using the average values measured in another study [9].

The number, time and good will of volunteers are generous but finite. This limits the volume of parameter space that may be investigated. For each subject, one measurement session investigated rates from 100 to 500 pulses per second (pps), applied between the three pairs of electrodes at the end of the array most distant from the round window. Five of the subjects returned for another experiment in which rates between 100 and 1000 pps were applied to three pairs of electrodes widely spaced along the array.

3 RESULTS AND DISCUSSION

Figure 2a shows the result for the experiment over the larger range of stimulation rates. At low frequencies, the pitch is strongly dependent on both rate and place but, at rates above several hundred pps, the stimulation rate has little effect and pitch decreases with distance from the round window.

Figure 2b shows the average of the scaled pitch for all subjects for the experiment with smaller rate and place range. The difference between electrodes at 15.5 mm and 16.3 mm is significant at 0.05, which suggests that the resolution of position in this context is less than or of the order of one electrode spacing (0.75 mm). The logarithmic dependence of pitch on rate invites comparison with normal hearing, where notes in the equal tempered chromatic scale of Western music

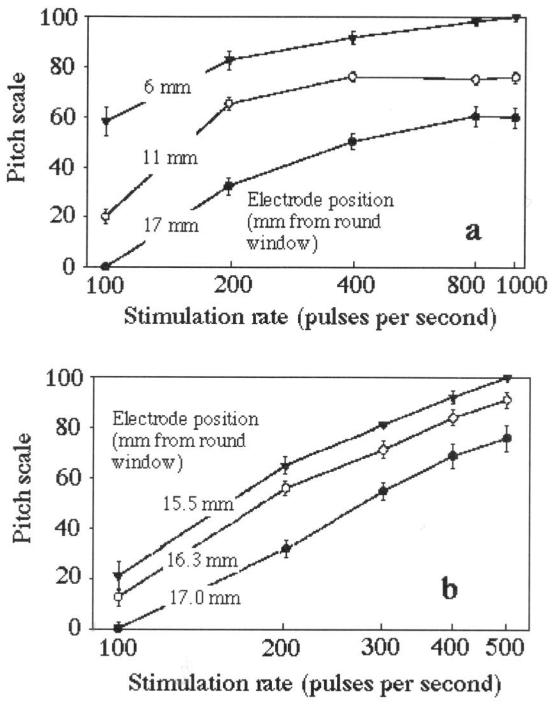

Figure 2. The average of the scaled pitch estimate (± s.e.) as a function of stimulation rate and electrode position. Higher number electrodes are inserted further into the cochlea (most distant from the window).

are equally spaced on a log frequency scale.

For the CI subjects, pitch also depends on place of stimulation, decreasing with distance from the round window. This can be compared with the tonotopic arrangement of the normal ear where a doubling in the frequency of the acoustic signal corresponded to a displacement of about 4 mm along the basilar membrane for frequencies above several hundred Hz, and smaller displacements for lower frequencies [10]. Because the pitch scales shown in Fig 2b are approximately logarithmically dependent on rate, we can calculate that a doubling in stimulation rate corresponds to a displacement of about 2 mm in this range. For the series of experiments reported in Fig 2a, the displacement corresponding to a doubling of stimulation rate depends on position and rate. It is about 4-6 mm at low rates and decreases for higher rates. The results for electrodes at 17 mm are slightly different between the two experiments. This may be due, in part, to the arbitrary nature of the pitch scale and the fact that the measurement sessions were conducted at different times. It is also possible that the task of assigning pitch is more difficult over a much larger range of the parameters.

The apparent saturation of the dependence of pitch on stimulation rate is not surprising at rates which are greater than the maximum firing rate of neurones. These results may not simply be compared with normal hearing, however, because the differential mechanical stimulation of hair cells is rather different from the electrical stimulation by the CI of many or all of the cells between or near the two electrodes. The influence of rate and place on pitch perception for these post-lingually deafened subjects nevertheless suggests that both rate and place are important in pitch coding for normal hearing at low frequencies, but that place alone dominates at sufficiently high frequencies.

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