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Pitch comparisons of acoustically and electrically evoked auditory sensations

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Abstract

Cochlear implant users with some residual hearing in the non-implanted ear compared the pitch sensations produced by acoustic pure tones and pulsatile electric stimuli. Pitch comparisons were obtained for pure tones and electrical stimuli presented at different positions (electrodes) in the scala tympani, keeping the electric pulse rate fixed at 100, 250, or 800 pps. Similarly, pitch comparisons were obtained for electrical stimuli with variable pulse rates presented to two fixed electrode positions (apical and basal) in the cochlea. Both electrode position and pulse rate influenced the perceived pitch of the electrical signal and 'matched' electric and acoustic signals were found over a wide range of frequencies. There was a large variation between listeners. For some stimuli, listeners had difficulty in deciding whether the acoustic or electric stimulus was higher in pitch. Despite the variability, consistent trends were obtained from the data: higher frequencies tended to be matched by more basal electrodes for all pulse rates. Higher frequencies tended to be matched by higher pulse rates for both electrode positions. The electrode positions that 'matched' pure tones were more basal than predicted from the characteristic frequency coordinates of the basilar membrane in a normal human cochlea.

Keywords: Cochlear prosthesis; Pitch; Electrical stimulation; Hearing impairment

1. Introduction

The pitch and timbre of electrically evoked hearing sensations are important for the perception of electrically coded speech and other sounds by cochlear implant users. They are also particularly interesting because the normal relationships between the physiological place and rate coding of acoustic stimuli, such as pure tones, do not apply to electric stimuli. For example, a 2 kHz pure tone in a normal ear will produce a maximum excitation at some point on the basilar membrane and the neurons at this point will be more sensitive to 2 kHz than to any other frequency. During excitation, the firing rate of this ensemble of neurons will be temporally modulated by the 2 kHz tone. In contrast, an electrode in the scala tympani may be situated at a position that would normally correspond to a characteristic frequency of 2 kHz, and be stimulated with an electric waveform that is pulsed with a rate of 100 Hz. In this case, one would normally assume that the site of maximum neural excitation would be close to the electrode, and that there would be no stimulation of nerves with a characteristic frequency of 100 Hz which are physically separated from the electrode by a distance of about 15 mm measured along the basilar membrane (Greenwood, 1961). Will this electric stimulus evoke a hearing sensation similar in pitch and timbre to a 2 kHz tone, a 100 Hz tone, a combination of these, or another acoustic stimulus? The most direct method of addressing these questions 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.

A question of nomenclature arises at this point. Strictly speaking, the word 'pitch' is used to describe the perceptual differences that arise when the fundamental frequency of a musical sound is changed, while other physical characteristics are held constant. These other characteristics include the broad spectral envelope of the sound which is often determined by the musical instrument producing the sound. The perceptual correlates of these other characteristics are described collectively as the 'timbre' of the sounds. Plomp and Steeneken (1971) have demonstrated

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that the perceptual correlates of fundamental frequency and spectral envelope characteristics are separate and orthogonal. It is also known that acoustic frequencies are coded physiologically in the temporal firing patterns of nerve fibers and in the spatial pattern of nerve excitation along the Organ of Corti (e.g., Evans, 1978). One might speculate that the temporal coding is responsible for the 'pitch' sensations and the spatial excitation pattern produces the perception of 'timbre'. When a pure tone is used as the stimulus, rather than a musical sound, the fundamental frequency is the only component of the sound, and clearly, the perceived 'pitch' changes as the frequency changes. However, the spectral envelope also changes, shifting the excitation pattern along the Organ of Corti as the pure-tone changes in frequency. Does this imply a change in 'timbre' as well? In the case of electrical stimuli, there is a temporal component of the stimulus, determined by its frequency or pulse rate, and there is a spatial component determined by the position and geometrical configuration of the electrodes in the cochlea. Tong et al. (1983) demonstrated that the perceptual correlates of pulse rate and electrode position were separate and orthogonal in an experiment analogous to the acoustic experiment of Plomp and Steeneken (1971). Again, one might speculate that the perceptual correlate of pulse rate is 'pitch' and the correlate of electrode position is 'timbre'.

Rather than pursuing the semantic and philosophical aspects of this discussion, we shall now concentrate on the practical implications for an experiment in which acoustic and electric signals are to be 'matched'. One could ask the listener to match the 'pitch' and/or the 'timbre' of an acoustic signal by varying the pulse rate and/or electrode position of an electric signal, assuming that this is possible. The first difficulty encountered will probably be that the listener, who has a severe-to-profound hearing loss and may be musically naive, will ask for an explanation of 'pitch' and 'timbre'. One may explain using the examples of musical notes and instruments as above, but this does not usually resolve the issue satisfactorily for the listener. One must also be careful not to introduce a preconceived notion that temporal characteristics of the electric signals correspond to 'pitch' and spatial characteristics to 'timbre', although one might hypothesize that this correspondence may emerge from the data. Apart from the ambiguity of these terms for the listener, there are some limitations inherent in the stimuli. As indicated above, pure tones may vary in both 'pitch' and 'timbre' as the frequency is changed. Secondly, there is no guarantee that either electric pulse rate or electrode position can be changed without affecting both 'pitch' and 'timbre' simultaneously. Thirdly, the neural excitation patterns produced by a continuous travelling wave on the basilar membrane and an electric current at a (more or less) localized position in the cochlea are likely to differ in the details of both their temporal and spatial characteristics. Thus it is unlikely that an exact match will be found for acoustic and electric stimuli, and there may be more than one electric stimulus that is considered to be matched in 'pitch' or 'timbre' to a particular acoustic stimulus. A pilot study with one listener who had considerable musical experience but had been profoundly hearing impaired for over 35 years indicated that a direct matching experiment that involved adjustment of pure-tone frequency, or electric pulse rate, or electrode position could result in a match that was acceptable to the listener. However, the listener reported difficulty in separating 'pitch' from 'timbre' and this was reflected in poor repeatability and wide spread in the 'matched' stimulus parameters. Despite the difficulty in achieving precise reliable matches, the listener was able to make comparisons of acoustic and electric stimuli on a scale from 'high' to 'low'. It is likely that both 'pitch' and 'timbre' differences contributed to these comparisons, but we described the task as a 'pitch comparison' task, and did not attempt to discuss the differences between 'pitch' and 'timbre' with the listeners. For simplicity, the word 'pitch' will be used below to describe the sensations experienced by the listeners. The knowledgable reader should bear in mind that the sensations are likely to be affected by 'timbre' as well as 'pitch' differences.

Three previous studies have investigated pitch matching of acoustic and electric signals. A study by Bilger (1977), using a bipolar electrode in the scala tympani, suggested that the frequency of sinusoidal acoustic stimuli could be matched by the frequency of an electric pulse train below 160 Hz. The electrode configuration did not allow variation of the position of electrical stimulation. Eddington et al. (1978b) reported pitch matching results for a unilaterally deaf volunteer. In the operating room, under local anaesthesia, the patient reported pitch matches between electric stimuli at 25 mm and 19 mm insertion depth with acoustic pure tones of 1500 and 2000 Hz, respectively. The electric pulse rate was 200 pps and the electrode configuration was monopolar (i.e., the electric current flowed between the intracochlear electrode and a remote electrode). Postoperatively, electric stimuli elicited 'fuzzy' sounds that were more difficult to match in pitch, but pitch differences could be estimated on a scale from -3 to $+3$. The experiment indicated pitch equivalence for an electric stimulus at 20 mm and an acoustic tone of 1225 Hz. A second equivalence was found at 16 mm and 1560 Hz. It is interesting that Eddington et al. (1978b) resorted to a relative pitch scaling method which is a more quantitative version of the pitch comparison method used in the present study, instead of a direct matching procedure. 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. Dorman et al. (1994) reported pitch matching data for low-frequency acoustic signals and sinusoidal electric signals presented to a single subject with the Ineraid cochlear implant. On the most apical electrode, the matched electric frequencies were slightly higher than the acoustic frequencies of 125, 200, and 300 Hz. When signals of fixed frequency were presented to electrodes located at successively more basal cochlear positions, pitch increased in an orderly fashion.

The majority of pitch and timbre studies have used methods that do not require direct comparisons of acoustic and electric stimuli. These methods include the discrimination, identification, and pitch scaling of electric stimuli differing in rate and or position of stimulation (Simmons, 1966; Eddington et al., 1978a,b; Tong et al., 1979, 1982, 1983; Tong and Clark, 1985; Shannon, 1983; Townshend et al., 1987; Dorman et al., 1990; Busby et al., 1994). In general, these studies have shown that perceived pitch increases as electric pulse rate increases and/or the electrode position is shifted in an apical-to-basal direction. The effect of pulse rate tends to weaken above 300 pps (Eddington et al., 1978a,b; Tong et al., 1979, 1983; Tong and Clark, 1985; Shannon, 1983) although some implant users have been reported to be sensitive to rate changes at higher frequencies (Simmons, 1966; Dorman et al., 1990). The distribution of electric current in the cochlea has also been varied by changing the electrode configuration (bipolar, monopolar, common ground, etc.) producing changes in the perceived pitch (Townshend et al., 1987; Busby et al., 1994). Few studies have explicitly addressed the issues of how rate and position of electric stimulation combine or interact. Some authors have suggested that there is a rate/place trade-off (e.g., Eddington et al., 1978b, Fig. 2) while others have suggested that position and rate have orthogonal effects on the perceived sound (e.g., Tong et al., 1983). The psychophysical results of Tong et al. were influential in the formulation of speech coding strategies in which the fundamental frequency of the voice was encoded using the electric pulse rate and the formant frequencies were encoded using electrode position in the cochlea. The latter suggestion is analogous to the effects of spectral shaping and fundamental frequency on the perception of harmonic tone complexes (Plomp and Steeneken, 1971) or spectral shaping and modulation frequency of amplitude modulated noise bands (Blamey et al., 1985). As explained above, we will use the word 'pitch' to denote the perceptual property (or properties) of electric stimuli that change when the pulse rate and/or electrode position is changed. Whether this perceptual property corresponds exactly to the usual notions of pitch and timbre is difficult to determine, but the experimental results may help to address the question.

Since the early pitch studies, cochlear implants have become well established as a means of providing auditory stimulation to people with profound hearing losses. Recent speech perception results of average post-linguistically deafened adult cochlear implant users are often higher than those for some hearing aid users with severe-to-profound hearing-impairments. For example, the average score on the CID Sentence Test (Silverman and Hirsh, 1955) without lipreading for post-linguistically deafened implant users with the Cochlear Pty Ltd. MSP speech processor 4–6 months postoperatively was 56% in the years 1990 to 1993 ($N = 32$) at the University of Melbourne/Royal Victorian Eye and Ear Hospital Cochlear Implant Clinic. More recently, the Cochlear Pty Ltd. SPECTRA-22 processor has boosted this average score to 78% ($N = 12$). This clinical experience has opened the way for cochlear implant use by people with some usable residual hearing in the non-implanted ear. This small group of implant users provides an opportunity to study the characteristics of electrically produced hearing sensations in direct comparison with acoustically produced hearing sensations, albeit in ears which have also suffered a severe-to-profound hearing loss.

The present study extends the pitch studies referred to above by using a direct comparison technique, applied with 13 cochlear implant users who have residual hearing in the non-implanted ear. Although this hearing is not ideal for our purpose as the non-implanted ears have severe-to-profound hearing losses, there is little evidence that impaired hearing thresholds are accompanied by large pitch or timbre changes for pure-tone stimuli. For example, the phenomenon of diplacusis has occasionally been reported in the literature (Davis et al., 1950; Schuknecht, 1970) but does not appear to be common among people with asymmetric hearing impairments. On the other hand, impaired frequency resolution and selectivity are more commonly reported (e.g., Zwicker and Schorn, 1978). Thus we may expect that hearing impairment is likely to produce a broader spread or uncertainty in the range of acceptable matches, relative to a similar hypothetical experiment in which the acoustically stimulated ears were normal.

The questions addressed in the study were: (1) whether it is possible to approximate the pitch of a pure-tone acoustic stimulus in one ear with an electric signal in the other ear; (2) whether the pulse rate of the matched electric stimulus would be equal to the frequency of the acoustic tone; (3) 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; and (4) whether the rate and position of the electric stimuli could be varied independently to produce a match to the pure tone.

2. Methods

2.1. Subjects

The subjects in this study were all post-linguistically deafened adults with a small amount of residual hearing in the non-implanted ear. Table 1 shows some of the audiological details for each subject. Subjects 1–3 were patients implanted at the University of Melbourne/Royal Victorian Eye and Ear Hospital Cochlear Implant Clinic. Subject 1 was available for psychophysical testing on a weekly basis and more data were collected for him than for the other

Table 1
Subject audiological details

Subject	Angular depth of insertion (degrees)	Hearing thresholds (dB HL re ANSI 1969)				
		250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
1	292	80	85	120↑	120↑	120↑
2	360 *	95	95	90	80	90
3	370 *	105↑	110	115	110	115
4	362	65	95	100	100	85
5	365	60	100	110	110	115↑
6	394	90	95	105	120	120↑
7	201	85	90	95	90	75
8	335	80	80	85	100	115↑
9	370	70	85	95	90	115
10	360 *	90	105	120↑	120↑	120↑
11	451	105↑	120↑	115	120	120↑
12	361	100↑	115	110	100	110
13	450 *	80	100	100	105	120↑

The angular depth of insertion refers to the most apical electrode in the cochlea.

* Estimated angle from depth of insertion reported by the surgeon.

↑ indicates that the threshold was higher than the limit of the audiometer level shown.

subjects. Subjects 4–13 were patients of the Denver Ear Institute who participated in two short periods of about 7 weeks each. All subjects were implanted with the 22-electrode cochlear implant (Clark et al., 1987). All subjects except subjects 1 and 3 were regular cochlear implant users who also wore their hearing aids most of the time. Subject 1 was an excellent lipreader and preferred to continue using his hearing aid alone because he reported that the implant interfered with his hearing aid use. Many combinations of different hearing aid and cochlear implant processor settings have been tried without finding a combination acceptable to subject 1 for long-term use. Subject 3 used her hearing aid very effectively pre-operatively, but found that it contributed nothing extra when used with the implant.

The care of humans reported on in this study was approved by the Australian National Health and Medical Research Council (Grant 930068, Psychophysics of Acoustic and Electric Signals in Opposite Ears).

2.2. Stimuli

Alternate acoustic and electric stimuli were produced by computer control of a 'bimodal' aid which incorporated a Cochlear implant speech processor (Seligman, 1987) and a hearing aid processor (Blamey et al., 1993). The electric signals were 500 ms trains of biphasic electric pulses at a fixed rate and produced on a single bipolar electrode pair. The acoustic stimuli were pure tones of duration 500 ms produced by exciting a low-pass filter with a square wave. The acoustic stimuli were presented via an Oticon AN1000 hearing aid receiver and ear mould at levels that were comfortable for the listener. The levels varied between subjects and between frequencies because of differences in thresholds and dynamic ranges. For a few subjects, it was not possible to achieve a loudness greater than 'soft' for some frequencies. Before starting a block of pitch comparisons, the intensity of each electric stimulus was adjusted to match the loudness of the acoustic stimulus.

2.3. Procedures

The procedures described below were developed after several pilot studies with subject 1. In some of these pilot studies, the subject was given control of one of the experimental variables (acoustic frequency, electric pulse rate, or electric position of stimulation) using a potentiometer knob, and asked to adjust the knob to produce the best match in pitch. The acoustic and electric stimuli were presented alternately with a 500 ms interstimulus interval. This adjustment procedure resulted in reports of matched pairs of stimuli, but unfortunately these were unreliable in that they could rarely be reproduced within a session or in different test sessions. A procedure using paired pitch comparisons and fixed stimulus parameters was developed in order to provide greater control over the experimental conditions. For each pair of stimuli, the subject was asked which was higher, and the judgements 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). Within a block of trials, only one of the three stimulus parameters was varied. This procedure produced relatively repeatable responses, although 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'. This procedure was then formalized as below and used with all subjects.

Two experiments were carried out. In the 'position experiment', the acoustic frequency and the electric pulse rate were held constant and the electrode position was varied to determine the cross-over point between 'acoustic higher' and 'electric higher' responses. In the 'rate experiment', the acoustic frequency and the electrode position were kept fixed and the electric pulse rate was varied.

For the position experiment, a subset of pure-tone frequencies was chosen for each subject, spanning the frequency range of usable hearing. The full set of frequencies was 250, 500, 750, 1000, 1250, 1500, 2000, 3000, and 4000 Hz. Three electric pulse rates were used: 100, 250, and 800 pps. Within a block of trials, the acoustic frequency and the electric pulse rate were kept fixed. The experimenter determined the sequence of electrode positions to be tested, with the aim of finding the position(s) along the electrode array where the acoustic and electric sounds were approximately matched in pitch. Every usable electrode was compared with the acoustic tone in at least one trial. In a single trial, the subject heard the acoustic and electric signals alternately in the two ears, and was asked which of the signals was 'higher'.

In the rate experiment the acoustic tones tested had frequencies of 65, 125, 250, 500, and 1000 Hz. An apical electrode and a basal electrode were tested for each subject. Within a block of trials the acoustic frequency and the electrode position were kept fixed. The experimenter determined the sequence of electric pulse rates to be tested, with the aim of finding the rate(s) where the acoustic and electric signals were approximately matched in pitch. The pulse rate was varied in the range from 50 pps to 1000 pps in steps of 25 Hz, but not every pulse rate was tested if a consistent pattern of responses emerged (see Section 3.1).

2.4. Determination of electrode positions

The surgical procedures involved in cochlear implantation can result in insertion of the electrodes to different depths in the scala tympani. Consequently, the electrode numbers used in programming the cochlear prosthesis (1–22) represent the ordering of electrodes (from basal to apical) but not their positions in the cochlea. To provide reliable position information, the subjects were asked to undergo an X-ray using a modified Stenver's view, with the intracochlear portion of the electrode array parallel to the plane of the film (Marsh et al., 1993). The X-rays were captured digitally and anatomical landmarks and electrode bands were marked by hand. These data were then used to determine the angular positions measured from the centre of the cochlear spiral, with the hook region of the basilar membrane at 0°. Angular positions were used in preference to depths of insertion because the position of the electrode array within the scala tympani is probably close to the outer wall of the cochlear spiral (Shepherd et al., 1993). Thus, distances along the array do not correspond directly to distances along the basilar membrane. Angular positions eliminate this discrepancy. Bredberg (1968) provides anatomical 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 Greenwood (1961) to calculate characteristic frequencies corresponding to angular positions in the cochleae of normally hearing listeners for comparison with the experimental pitch matching results. Four subjects (numbers 2, 3, 10 and 13) declined to have X-rays, and angular positions were estimated from the depth of electrode insertion reported at the time of surgery.

3. Results

3.1. Data analysis

The first stage of analysis was to test each block of data to see how well the data fitted a monotonic pitch relationship. We would expect the pitch of an electric stimulus to increase monotonically as the position of stimulation is moved along the scala tympani in an apical to basal direction. Thus it is reasonable to expect a pattern of responses which changes from 'acoustic higher' to 'electric higher' as the electrode position becomes more basal in the position experiment. To illustrate the analysis method, Table 2a shows a typical block of responses from the position experiment. The expected pattern will be obvious to the reader, although there is a fairly wide range of electrodes (from electrode 4 to 11) where the responses were a mixture of 'electric higher', 'acoustic higher' and 'both the same'. The strength of the pattern was assessed by assigning values of 1 to 3 to the responses 'acoustic higher', 'both the same', and 'electric higher', respectively, and calculating the Spearman rank correlation coefficient for the response value and the electrode number. If there was no significant correlation ($P > 0.05$), it was assumed that the expected pattern was not present. The rank correlation coefficient and P value derived from Table 2a was $r = -0.74$, $P < 0.0005$. Table 2b shows a block of responses from the rate experiment, where one would expect a monotonic increase in the pitch of the electric stimuli as the rate increases. The transition from 'acoustic higher' to 'electric higher' is very well defined for the data in Table 2b. For the rate experiment data, rank correlations for response values as above and electric pulse rates were calculated. This resulted in $r = 0.85$, $P <$

Table 2
Examples of responses from a single block of trials, shown to illustrate the analysis methods

(a)		(b)		(c)	
Electrode	Response(s)	Pulse rate	Response(s)	Electrode	Response(s)
20	A,A	50	A,A	20	A
19	A	75		19	
18	A	100	A,A	18	
17	A	125		17	A
16	A	150	A,A	16	S
15	A,A	175	A,A	15	E
14	A	200	E,A,E	14	E
13	A	225	E,E	13	E
12	A,A	250	E,E	12	A,E
11	S,E	275		11	A
10	A,E	300	E,E	10	A,A
9	S,S,E	325		9	A,A
8	A,E	350		8	A,S
7	S,E	375		7	A,S
6	A,E	400	E,E	6	A,S,S
5	S,E	425		5	A,E,E
4	S,E	450		4	A,E
3	E,E	475		3	E,E
2	E	500	E,E	2	E
1	E	525		1	

A, acoustic higher; S, both the same; E, electric higher.
The data in (a) were for an acoustic pure tone of 1 kHz and an electric pulse rate of 250 pps for Subject 1. The data in (b) were for an acoustic tone of 250 Hz and an electric signal on electrode 20 (the most apical electrode) for Subject 10. The data in (c) were for an acoustic tone of 500 Hz and an electric pulse rate of 250 pps for Subject 12.

Table 3
Summary of Spearman rank correlation coefficient analysis

Experiment	Group A	Group B	Group C	Total
position (100 pps)	2	7	26	35
position (250 pps)	6	12	40	58
position (800 pps)	2	10	34	46
position (all rates)	10	29	100	139
rate (apical electrode)	0	9	27	36
rate (basal electrode)	0	11	20	31
rate (both electrodes)	0	20	47	67
position & rate total	10	49	147	206

In Group A response blocks had more than two of each 'acoustic higher' and 'electric higher' responses, but a non-significant correlation ($P > 0.05$) between response type and electrode (position experiment) or pulse rate (rate experiment), indicating that the expected pattern of responses did not occur.

In group B response blocks had fewer than two 'acoustic higher' or fewer than two 'electric higher' responses, possibly indicating that the best matching condition was outside the range tested.

In group C response blocks had significant correlation coefficients ($P < 0.05$) indicating that the expected pattern of responses was present.

0.00001 for Table 2b. Table 2c gives an example where the correlation coefficient was not significant ($r = 0.27$, $P = 0.08$). For this block of responses there seem to be two distinct regions where the electric stimulus was higher and two where the acoustic stimulus was higher. This result is discussed in more detail later. The most common reason for obtaining a non-significant correlation was that in some response blocks, the electric stimuli were either nearly always higher, or nearly always lower than the acoustic stimulus used. Although these latter response blocks do not give a significant correlation, they are not necessarily inconsistent with the existence of a matching electric stimulus outside the range used in the present experiments. In this case, the best that can be done is to put an upper or lower limit on the parameters required to produce a matching electric stimulus. Table 3 classifies all of the response blocks into those which are not consistent with the expected response pattern, those for which a possible match might exist outside the tested range, and those for which a significant correlation was found. The different totals (shown in the last column) for the experimental conditions arose from the time limit on testing subjects during the two short visits to Denver. Five of the subjects were tested at only two pulse rates in the position experiment, and one subject was tested with only one electrode in the rate experiment.

The second stage of analysis used a least-squares fitting procedure to determine the electrode of best match (position experiment) or the pulse rate of best match (rate experiment) for each response block. The analysis procedure minimized the squared difference between the best match and each stimulus summed over all 'both the same' responses and all responses that were on the 'wrong' side of the best match. In the position experiment, 'wrong' responses consisted of 'electric higher' for electrodes that were more apical than the best-matched electrode and 'acoustic higher' for electrodes that were more basal. For example, the electrode of best match for the data in Table 2a was number 8. Similarly in the rate experiment, 'wrong' responses were 'electric higher' for pulse rates that were lower than the best match, and 'acoustic higher' for pulse rates that were higher. The rate of best match for Table 2b was 200 pps. No best match was calculated from Table 2c because the correlation between electrode and response was non-significant.

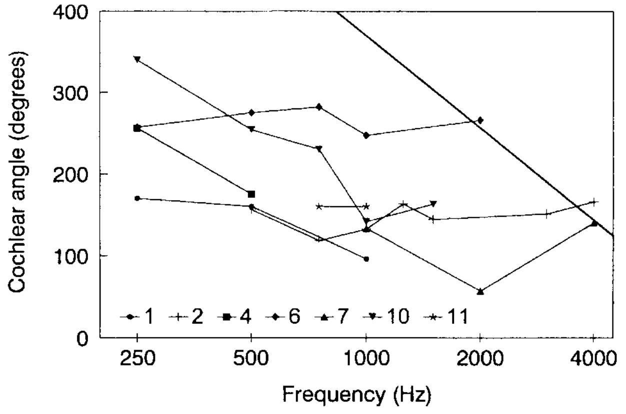

Fig. 1. Best-matched electrodes for an electric pulse rate of 100 pps as a function of acoustic pure tone frequency from the position experiment. The electrode position is given in terms of the angle measured about the axis of the cochlear spiral from a zero at the hook region of the basilar membrane.

3.2. Position experiment

All subjects apart from Subjects 3 and 13 participated in the position experiment. Figs. 1–3 show the best-match positions for the individual subjects as a function of pure-tone frequency for pulse rates 100, 250, and 800 pps, respectively. It should be noted that it was not possible to collect complete data for all subjects because of insufficient residual hearing at some frequencies and because of

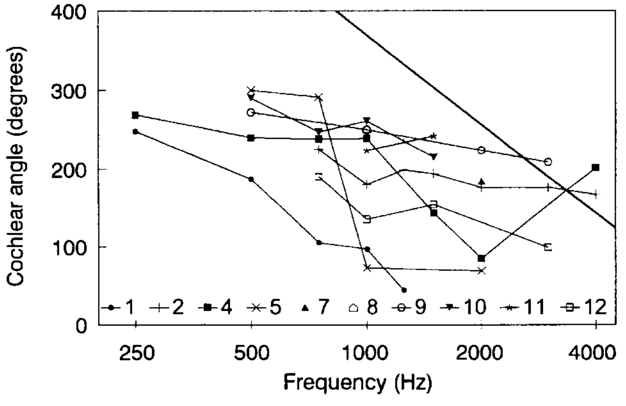

Fig. 2. Best-matched electrodes for an electric pulse rate of 250 pps as a function of acoustic pure tone frequency from the position experiment.

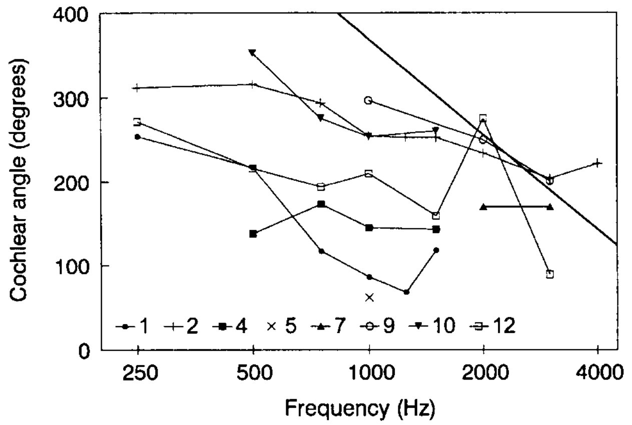

Fig. 3. Best-matched electrodes for an electric pulse rate of 800 pps as a function of acoustic pure tone frequency from the position experiment.

time constraints. Response blocks which did not show a significant Spearman rank correlation in the first stage of analysis were also excluded from the figures. The symbols used to represent individual subjects' data are kept fixed for all the figures to facilitate comparisons. The heavy solid line in Figs. 1–3 represents the angular positions of points on the basilar membrane that correspond to pure-tone frequencies in normally hearing listeners (Greenwood, 1961; Bredberg, 1968). Despite a broad spread of results across subjects, it is clear that the angular positions for electric stimuli that match pure tones are more basal than in a normal cochlea for frequencies below 2 kHz.

3.3. Rate experiment

Subjects 1, 3–7, 10 and 13 participated in the rate experiment. Figs. 4 and 5 show the best-match rates for individual subjects as a function of the pure-tone frequency for an apical and a basal electrode respectively. Response blocks which did not show a significant Spearman rank correlation in the first stage of analysis were excluded from the figures. The heavy solid lines in Figs. 4 and 5 represent equal pure-tone frequency and electric pulse rate. Most points lie within 1 octave of the heavy line, although there is a tendency for points at low frequencies to lie above the line, and points at high frequencies to fall below the line.

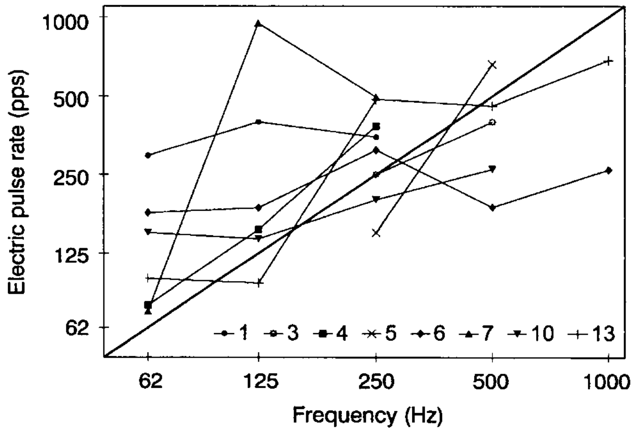

Fig. 4. Best-matched pulse rates for an apical electrode as a function of acoustic pure tone frequency from the rate experiment.

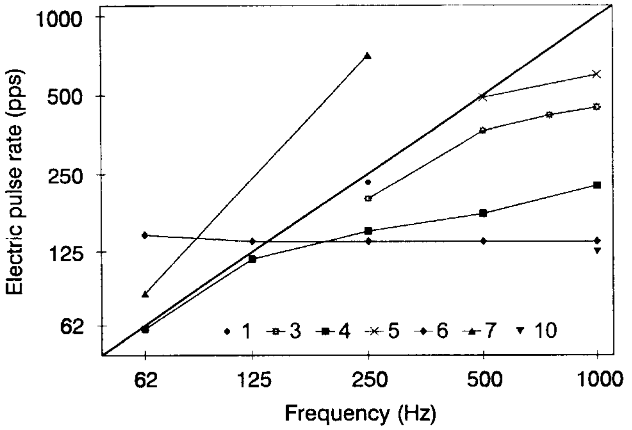

Fig. 5. Best-matched pulse rates for a basal electrode as a function of acoustic pure tone frequency from the rate experiment.

4. Discussion

4.1. Is it possible to approximate the pitch of an acoustic tone by varying the position of an electric signal?

The answer to this question is yes, but the subjects found it to be a difficult task. This difficulty was reflected in the broad regions of uncertainty in which electrical stimuli were reported to have the same pitch as an acoustic tone, or in which the subjects' responses included a mixture of both 'acoustic higher' and 'electric higher'. Table 2a gives an example where the region of uncertainty spans 8 electrodes (4–11). In the position experiment, the mean region of uncertainty spanned 5.7 electrodes, corresponding to a distance of 4 mm and subtending an angle of about 70° at the centre of the cochlear spiral. The difficulty of the task is also shown by the fact that 28% of the response blocks did not result in acceptable best matches (group A, Table 3). A chi-squared analysis of the proportions of response blocks falling into groups A, B, and C did not indicate any significant differences between the three pulse rates used in the position experiment ($\chi^2 = 0.82$, $df = 4$, ns). Thus the matching task was equally difficult for each rate.

4.2. Is it possible to approximate the pitch of an acoustic tone by varying the pulse rate of an electric signal?

The answer to this question is also yes, but the task was difficult for the listeners. Seventy percent of the response blocks resulted in acceptable best matches (Table 3). A chi-squared analysis indicated no significant difference between the proportions of acceptable matches for the apical and basal electrodes ($\chi^2 = 0.87$, $df = 1$, ns). No response blocks fell into group A (incompatible with the expected pattern of increasing pitch as pulse rate increased). In ten cases where a 'best match' was found, the region of uncertainty was very large. These cases all had regions of low electric pulse rate where the electric stimulus was consistently reported to be lower in pitch than the acoustic tone, but had no well-defined region where the electric stimulus was consistently reported to be higher in pitch. This result is consistent with earlier reports (Eddington et al., 1978a,b; Tong et al., 1979, 1983; Tong and Clark, 1985; Simmons et al., 1965; Shannon, 1983) that the effect of electric pulse rate becomes weaker above about 300 pps than it is at lower rates. Leaving aside these cases where no upper bound could be estimated for the best-matched pulse rate, the mean region of uncertainty was 107 pps or 0.4 octaves wide.

A chi-squared analysis indicated a significant difference in the proportions of response blocks in groups A, B, and C between the position and rate experiments ($\chi^2 = 6.38$, $df = 2$, $P < 0.05$). Two effects contributed to this result. Firstly, the variation of pulse rate did not result in any anomalous (group A) response patterns, but the variation of electrode position gave anomalous response patterns in 7% of cases. Secondly, a greater proportion of cases in the rate experiment resulted in no upper or lower bound to the matching region (group B). Thus the variation of pitch with electric pulse rate is more monotonic and predictable, but spans a narrower range than the variation of pitch with electrode position. As one anonymous reviewer suggested, the periodicity of neural firing patterns (< 1000 Hz) is well-defined by the periodicity of the stimulus whether it is acoustic or electric. In contrast, the spatial distributions of excitation may be very different for electric and acoustic stimuli. This may help to explain why anomalous response patterns were found in the position experiment, but not in the rate experiment.

4.3. Does the best-matched electrode position correspond to the place of maximum excitation produced by the acoustic tone?

The heavy solid lines in Figs. 1–3 represent the angular positions of points on the basilar membrane that correspond to pure-tone frequencies in normally hearing listeners (Greenwood, 1961; Bredberg, 1968). It is clear from Figs. 1–3 that the points for low-frequency matches are displaced well to the left of the line representing the frequency to place function for normally hearing listeners. In other words, the pitch percept evoked by electrical stimulation with an electrode at a given position in the cochlea may correspond to a tone up to 3 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 for normally hearing listeners. The lines connecting best matches for most subjects, and the overall trends of the data indicate a downward slope from left to right, but the slopes are smaller than for the normally hearing function. The variation of angle with frequency, averaged over all subjects shown in Figs. 1–3, is −48°/octave, compared with −109°/octave for listeners with normal hearing [1]. This means that perceived pitch varies more rapidly with position for electrical stimulation than for acoustic stimulation.

Table 4
Classification of stimulus comparisons where the electrode was situated at the position of maximum excitation of the basilar membrane in a normal human cochlea (Greenwood, 1961; Bredberg, 1968)

Response	Frequency (Hz)									
	250	500	750	1000	1250	1500	2000	3000	4000	Total
E	0	0	0	1	0	0	2	3	4	10
S	0	0	1	3	0	2	3	5	3	17
A	6	12	16	21	5	13	8	4	0	85
Total	6	12	17	25	5	15	13	12	7	112

Response 'E' indicates the electric signal was higher in pitch, 'A' indicates acoustic higher, and 'S' indicates both had the same pitch.

The discussion in the previous paragraph relies heavily on the data analysis procedure for determining the best matching electrode, and ignores some of the detail of the raw data, such as the fairly wide regions of uncertainty that have been mentioned above. It is possible to address the question of whether the pitch of the electrical stimulus is higher or lower than expected by a more direct analysis. For each acoustic tone used, the position of the maximum of excitation in a normal cochlea was calculated according to Greenwood (1961) and Bredberg (1968). The electrode closest to this position was determined, and the responses for this electrode were classified as A (acoustic higher), E (electric higher), or S (same). If the calculated position of maximum excitation was more apical than the most apical electrode, and the response for this electrode was A, it was assumed that an electrode at the position of maximum acoustic excitation would also be lower than the acoustic tone. Table 4 shows the response distributions as a function of acoustic frequency for the electrodes closest to the point of maximum acoustic excitation, combined for all subjects and all pulse rates. A chi-squared analysis indicates a significant effect of frequency ($\chi^2 = 53.6$, $df = 16$, $P < 0.001$), and inspection of Table 4 shows that the subjects consistently reported lower than expected pitch for electrodes at positions of maximum acoustic excitation for frequencies below 2 kHz.

There are several factors that may contribute to the result that the perceived pitch is considerably lower than

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[1] In an earlier conference proceedings (Blamey et al., 1995), an incorrect value of −88°/octave was reported as the slope of the regression line for all data at 250 pps. This was the value for a single subject (#1), not the average of all subjects as reported here.

would be predicted from studies of normal ears. First, the pitch comparisons were between acoustic stimuli in a severely-to-profoundly impaired ear and an electrically stimulated ear. It is known that the point of maximum excitation in a severely impaired ear is shifted by 0.5–1 octave relative to a normal ear (Sellick et al., 1982). This would correspond to a shift of the solid line in Figs. 1–3 by up to 1 octave to the left. This would improve the fit to the data in the mid-frequency region, but not at low frequencies, and would not account for the differences in slope between the data and the predicted line. In any case, it has not been reported in the literature (as far as the authors are aware) that the shift in the position of maximum excitation produces any change in the perceived pitch of the acoustic stimulus. Zwislocki (1991) pointed out that there is a shift in the position of maximum excitation for normal ears stimulated with loud tones. The shift may be equivalent to a frequency change of up to 1 octave, but does not produce a corresponding octave pitch change. Zwislocki suggested that the apical edge of the region of excitation may be the spatial factor that determines the pitch of the sound, instead of the point of maximum excitation. Again, this might account for a shift between the data and the predicted line, although one would need to apply the same reasoning to both the electrical excitation pattern and the acoustic excitation pattern. If the apical cut-off is sharper for acoustic stimuli than for electric stimuli, the effect might help to explain the lower than expected pitch for electric stimuli, but this factor would not account for the difference in slope. A broad cut-off in the electric case might also account for the wide range of acceptable matches found in the position matching experiment.

Another possibility is that the listeners may have adapted to the sounds that they hear through the implant and hearing aid in everyday life so that simultaneously occurring sounds in the two ears are perceived as having the same pitch. In other words, the perceptual system may have learned to compensate for any pitch differences that may have been present immediately after implantation. If this process was complete, the acoustic frequency matched to each electrode would correspond to the frequency that was usually mapped onto that electrode by the real-time speech processor. This did not seem to be the case for most of the subjects (Fig. 6).

The actual site of excitation of the nerves is also important in determining the neural excitation pattern. It is known that there are few surviving dendrites (Hinojosa and Lindsay, 1980; Nadol et al., 1989), and that the site of excitation is probably in Rosenthal's Canal. It is also known that the dendrites do not travel radially outwards from Rosenthal's Canal, and that the ganglion cells in the modiolus extend around 1.875 turns compared to 2.625 turns for the Organ of Corti (Kawano et al., 1996). Thus the ganglion cells normally responding to a given acoustic frequency may be situated in a position that is more basal than the point of maximum excitation of the basilar membrane. To a first approximation, one would expect the variation of angle versus characteristic frequency for spiral ganglion cell bodies to be $-78°$/octave (i.e., $-109°$/octave × 1.875/2.625). This is closer to the observed slope of $-48°$/octave in Figs. 1–3, but probably does not account for the full effect.

Finally, the effect of the possible low-pitched component corresponding to the pulse rate of the electric stimulus should be considered. The effect of this component on the pitch comparisons is difficult to predict. The interaction of pulse rate and electrode position is discussed at greater length below.

4.4. Does the best-matched electric pulse rate correspond to the frequency of the acoustic tone?

In the rate 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. The slopes of regression lines for Figs. 4 and 5 are 0.36 and 0.34, respectively. These slopes are both significantly different from 1.0 ($P < 0.01$). The slope values indicate that pitch increased more rapidly as a function of pulse rate than as a function of frequency in the range of this experiment (i.e., the frequency change required to match a given change in pulse rate was greater than the pulse rate change). This is consistent with electric pitch scaling results (Tong et al., 1979, 1983; Shannon, 1983) and a comparison with pitch scaling by normally hearing listeners (Blamey et al., 1985). As one anonymous reviewer pointed out, the finding that electrical periodicity pitch is not identical to acoustic periodicity pitch suggests that simple periodicity is not an adequate code for pitch.

Table 5 gives results for direct comparisons where the acoustic frequency was equal to the electric pulse rate. A chi-squared analysis showed a significant variation of the response distributions with frequency for the most apical electrode ($\chi^2 = 20.9$, $df = 8$, $P < 0.01$), and inspection of Table 5 indicates that the electrical stimuli were lower in

Table 5
Classification of stimulus comparisons with equal acoustic frequency and electric pulse rate

		Frequency (Hz) and pulse rate (pps)					
Electrode	Response	65	125	250	500	1000	Total
Apical	E	0	0	4	4	2	10
	S	4	5	10	6	2	27
	A	6	7	0	4	8	25
	Total	10	12	14	14	12	62
Basal	E	4	4	7	6	4	25
	S	2	2	2	2	2	10
	A	3	3	2	4	2	14
	Total	9	9	11	12	8	49

'E', 'S' and 'A' codes are as for Table 4.

pitch than the corresponding acoustic stimuli at 62 and 125 Hz, and symmetrically spread above and below the acoustic signal at 250, 500, and 1000 Hz. At the most basal electrode, there was no significant difference between the response distributions at different frequencies ($\chi^2 = 1.41$, $df = 8$, ns). Comparison of the total response distributions from the two electrodes indicated that a greater proportion of the comparisons for the basal electrode resulted in an Electric higher response, as expected ($\chi^2 = 16.04$, $df = 2$, $P < 0.001$).

Some of the variability across listeners may reflect the relatively poor frequency tuning that is to be expected in the severely-to-profoundly impaired non-implanted ears (Zwicker and Schorn, 1978), and the poor rate discrimination in the implanted ear (Tong et al., 1982; Blamey et al., 1985). 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 electrodes. The next section discusses the interaction of pulse rate and electrode position at greater length.

4.5. Can the rate and position of the electrical stimuli be varied independently to produce a match to the pure tone?

The results indicate that both rate and position of electrical stimuli affected the pitch over quite broad ranges, and there was a significant difference between the best-matched electrodes obtained at rates of 100, 250 and 800 pps (Figs. 1–3). A paired t-test indicated that the best-matched electrodes for a rate of 250 pps were significantly more apical than those for 100 pps ($t = 5.42$, $P < 0.0001$, $df = 15$), and that the best-matched electrodes for 800 pps were significantly more apical than those for 100 pps ($t = 5.56$, $P < 0.0001$, $df = 14$). The best-matched electrodes for 800 pps were marginally more apical than those for 250 pps ($t = 1.91$, $P = 0.067$, $df = 27$). Similarly, the best-matched pulse rates obtained on the most basal electrode were significantly lower than those obtained for the most apical electrode ($t = 2.16$, $P < 0.05$, $df = 13$). Thus, positive changes in pulse rates were compensated to some extent by changes toward lower pitched electrodes and vice versa.

In 75 cases, comparisons between acoustic and electric stimuli were replicated in the position and rate experiments. Twelve of these cases resulted in contradictory responses from the two experiments (i.e., the electric stimulus was reliably reported as higher in one experiment, and lower in the other experiment). All 12 contradictions occurred for electric stimuli on the most basal (highest pitch) electrode and nine occurred for the lowest pulse rate (100 pps) used in the position experiment. All 12 contradictions involved judgements that the electric stimulus was higher in the position experiment and lower in the rate experiment. Thus, contradictions were most likely to occur when the rate and position effects were separated by the maximum amount, and the listener's attention was focused on those aspects of the electrical stimuli that were changing within an experimental block. This is consistent with the result of Tong et al. (1983) showing that rate and position had separate orthogonal effects on the perception of electric stimuli. Thus the parameter that was kept fixed would have had a small, but constant effect on the matching results in each block of comparisons. Contradictory pitch judgments can also occur in experiments with complex acoustic stimuli (e.g., Shepard, 1964).

The results of Tong et al. (1983) may be interpreted in two distinct ways. Either there are separate qualities of the sensation associated with the rate and position parameters (such as the 'pitch' and 'timbre' qualities discussed in the introduction), or there are two components corresponding to the rate and position of stimulation, each of which has a pitch (like a tone complex with two components). In the former case, one would not expect much trade-off between rate and position. In the latter case, rate and position would both affect the perceived pitch, and depending on the listener's method of assigning a combined pitch to the complex, there could be a considerable trade-off between rate and position in the present experiments. The latter option also seems to fit better with the broad ranges of same responses and the fact that some of the blocks of comparisons indicated multiple matches for electrode position (group A in Table 3; example c in Table 2). Some listeners provided unsolicited, very explicit descriptions of the stimuli. For example, a low rate stimulus on a basal electrode prompted subject 1 to say he could hear 'individual bursts at a slow rate', so that he 'knew it was lower than the pure tone, but each burst also sounded high pitched'. On a few occasions, some listeners reported hearing two components in the electric signal. Two listeners reported a few 'perfect' matches where the acoustic and electric signals were indistinguishable, but this was not usually possible. Thus it is unlikely that a single pure tone is a good model for the sensation produced by a pulsatile electric signal on a single electrode pair.

4.6. Implications for frequency mapping

In the implant speech processor, frequency bands are 'mapped' to particular electrodes, and the fundamental frequency of the voice, F0, is represented by the pulse rate or amplitude modulation within frequency bands. If the pitch of an electric stimulus had approximated the pitch of a pure tone which produces a maximum of excitation on the basilar membrane at the corresponding position in a normally hearing listener as shown by the heavy lines in Figs. 1–3, the mapping of frequencies from 300 Hz to 6 kHz onto electrodes in the basal turn of the cochlea

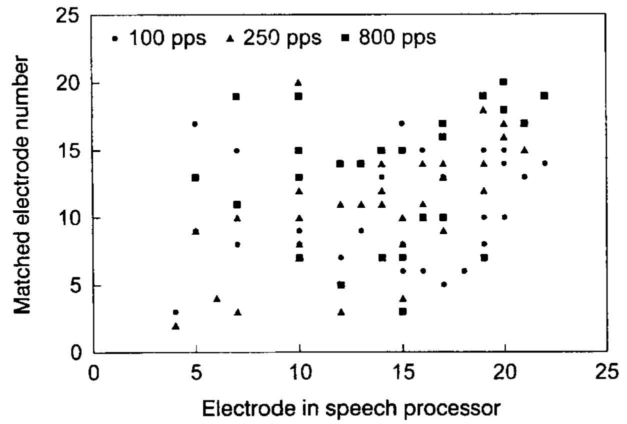

Fig. 6. Best-matched electrodes plotted against the electrodes that correspond to the matching frequency from the speech processor maps. If patients had learned a correspondence between electrode position and frequency by listening to the implant and hearing aid together, one would expect the points in this figure to lie on the diagonal.

(0–360° in Figs. 1–3) would have implied a considerable upward pitch shift. The results of the position experiment imply that the perceived pitch range for many implant users is actually quite close to the normal range covered by speech stimuli. Patients with a relatively shallow electrode insertion will still experience an upward pitch shift, but usually less than 1 octave. The size of this perceptual shift would be similar to the difference between adult and child voices, and thus within the usual range of variability experienced by normally hearing listeners. This result helps to explain why most post-linguistically deafened 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 (Whitford et al., 1993). In addition, 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 F0 if they are represented as pulse rates.

5. Conclusions

The results of these experiments are in general agreement with previous studies of pitch perception in cochlear implant users carried out with different methods. They show that both pulse rate and electrode position influence the perceived pitch, and that there are possibly two perceptual components of the electrically evoked sound. The pitch arising from the electrode position parameter is much lower than expected for electrodes inserted more than about half a turn into the cochlea. The most likely explanation for this is that the site of electrical stimulation is the ganglion cell body in Rosenthal's Canal, where the full range of characteristic frequencies is spanned by 1.875 turns instead of the 2.625 turns of the basilar membrane. The perceptual effect is fortuitous for speech coding because it allows a more natural coding of low-frequency speech components without the need to insert electrodes into the most apical parts of the cochlea.

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