UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

University of Southampton Auditory Implant Service
Institute of Sound and Vibration Research

Optimising Frequency-to-Electrode Allocation for Individual Cochlear Implant Users

by

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ABSTRACT

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OPTIMISING FREQUENCY-TO-ELECTRODE ALLOCATION FOR INDIVIDUAL COCHLEAR IMPLANT USERS

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Pitch perception for cochlear implant (CI) users is known to vary between individuals due to differences of insertion depth, of the function of neural tissue in the cochlea, of acclimatisation and CI stimulation parameters. In this study, frequency-to-electrode allocation was adjusted in a group of 12 adult cochlear implant users, to ascertain if the use of a default setting results in optimum perception of speech and music for individual recipients. Participants in the experiment trialled a map in which the frequency allocation was adjusted to the frequency-position function of the normal cochlea and a map which allocated sounds to a limited area of the cochlea, in addition to the default. Performance with the two alternative maps did not exceed that of the default allocation and was poorer for the majority of participants: [$F(2,14) = 51.3$, $p<0.001$] for a sentence test in noise. Performance was negatively correlated with the magnitude of the adjustment from the default [r=0.838, p=0.002 and r=-0.700, p=0.024] for the two maps, suggesting that participants had acclimatised to their clinical maps. Electrode discrimination was found to be at chance levels for some participants at the apical end of the array but above chance in the middle of the array. Another alternative map, with logarithmic frequency spacing and some basal shift was trialled and gave improved performance on a sentence test in noise for three participants with poor electrode discrimination at the apical end of the array.

A second experiment was conducted, with 13 adult CI users, in which perception of speech and music was assessed with ten frequency allocations, including the default. The ability to follow a pitch contour was measured for centre frequencies of neighbouring filters. Performance with the different allocations varied between individuals; some individuals performed better with alternative allocations from the default. A strategy was developed for the selection of frequency allocation for individuals, based on pitch contour scores for different electrodes, which offered improved performance on the sentence test for the group [$t(12)$=-3.31, p=0.006, r=0.69]. The overall results show that optimisation of frequency allocation for individuals can be achieved by adjustment of the frequency-to-electrode allocation based on pitch perception ability in different areas of the cochlea.

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DECLARATION OF AUTHORSHIP

I, Mary Louise Grasmeder declare that this thesis **'Optimising Frequency-to-Electrode Allocation for Individual Cochlear Implant Users'** and the work presented in it, are my own and have been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:

GRASMEDER, M. L., VERSCHUUR, C. A. & BATTY, V. B. 2014. Optimizing frequency-to-electrode allocation for individual cochlear implant users. *Journal of the Acoustical Society of America,* 136**,** 3313-3324.

The main body of this paper can be found in Appendix 1.

GRASMEDER, M. L. & VERSCHUUR, C. A. 2015. Perception of the pitch and naturalness of popular music by cochlear implant users. *Cochlear implants international,* 16 Suppl 3**,** S79-90.

The main body of this paper can be found in Appendix 2.

Signed:...

Date:..

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Definitions and Abbreviations

3I3AFC 3-interval, 3-alternative forced choice: type of test in which three stimuli are presented and there are three possible answers

AB Advanced Bionics, cochlear implant manufacturer

ANOVA analysis of variance

ANCOVA analysis of co-variance

BIF band importance function, refers to the relative importance of a frequency band in comparison to that of other frequency bands

CI cochlear implant

CT computed tomography

dB decibel

E electrode

e.g. for example

F0 fundamental frequency

F1 first formant

F2 second formant

FIR finite impulse response, a type of filter used in signal processing to separate sounds of different frequency

FS fine structure

GUI graphical user interface

HD-CIS high definition continuous interleaved sampling, a speech processing strategy used in cochlear implants

Hz Hertz

IMAP Interactive Music Awareness Programme (a rehabilitation program for CI users)

MED-EL a cochlear implant manufacturer

N	number of participants
Nucleus	a cochlear implant manufacturer
OC	organ of Corti
RAU	rationalised arcsine unit
s	seconds
SG	spiral ganglion
SII	Speech Intelligibility Index
SNR	signal-to-noise ratio
SSCC	superior semi-circular canal

Chapter 1: Overall Structure and Contribution to Knowledge

1.1 Structure of this thesis

This thesis has investigated different methods of adjustment of the frequency-to-electrode allocation for unilaterally implanted adult cochlear implant (CI) users. Assessment of pitch perception has also been undertaken for adjacent electrodes along the array.

The thesis commences in Chapter 2 with an introduction, detailing previous work in relation to the perception of speech, music and pitch for CI users, and how these are affected by the position of electrodes, the function of neural tissue within the cochlea, acclimatisation, temporal pitch cues and tuning parameters, particularly frequency-to-electrode allocation.

Chapter 3 describes an experiment in which adjustments to the frequency allocation were made based on insertion angle measurements. Two alternative allocations were compared to participants' clinical maps, one of which attempted to assign frequencies for implant users to the place of maximum excitation for sounds of the same frequency within the normal cochlea. The other alternative allocation restricted the stimulation to a limited area of the cochlea, which may be more suitable for impaired cochleae. Electrode discrimination was also measured.

Chapter 4 describes an additional allocation which was trialled within the same experiment, in which the frequency range was reduced when compared to the default range and logarithmic spacing of filter bandwidths was introduced. This led on to a second experiment which is detailed in Chapter 5. The second experiment was also concerned with the adjustment of frequency allocation, this time in relation to pitch perception along the array; the effect of pitch perception for different electrodes was analysed alongside performance with ten different frequency allocations on measures of speech and music perception.

A discussion of the outcomes of the study is contained in Chapter 6, alongside recommendations for further work, including the introduction of a new strategy for selecting a suitable frequency allocation for individual CI users based on results with the 'Pitch Contour Test' for different electrodes. Finally, the conclusions can be found in Chapter 7.

1.2 Novel Contribution to Knowledge

This thesis has contributed new information to the CI literature in relation to novel assessments for pitch perception, music perception, insertion angle estimation and the clinical use of a vowel identification test. Measures of performance with different frequency allocations have contributed to knowledge relating to optimising tuning for CI users.

In the first experiment, there were developments in methodology relating to the estimation of insertion angles from routine post-operative X-rays. The extent to which the relative positions of the most apical and basal intra-cochlear electrodes could be used to estimate the insertion angles of all the available electrodes was investigated. Further details are given in section 3.1.3. Secondly, a new method for measuring electrode discrimination was introduced, which could be performed with the manufacturer's normal tuning software, without the need to stimulate the implant directly. Pure tones were presented via circumaural headphones, whilst a map was activated in the manufacturer's standard fitting software, which allowed the pure tones used in the test to be perceived on adjacent electrodes. Further details are given in section 3.1.11.

In the second experiment, novel methods for the assessment of pitch perception were introduced. For example, the ability to follow a simple pitch contour was assessed using a new test known as the 'Pitch Contour Test' (PCT), which was configured to enable neighbouring electrodes to be tested in this way. The test was validated for this purpose as part of this study. Another new assessment required CI users to correct the pitch of a song following adjustment of their implant's frequency allocation. A computer program which incorporates a pitch slider, allowing the pitch of a song to be adjusted in real time, was used for this purpose. More details of these assessments are given in Chapter 5. In addition, an eight alternative forced choice test was used to assess vowel recognition, which is not used in routine clinical practice. This identified specific confusions between vowel sounds, which would not have been found using a standard clinical sentence test.

Different approaches to adjusting frequency allocation were compared, offering new insights in this area. The approaches compared were firstly the use of a default allocation, which is the same for all CI users. Secondly, the use of fixed-position frequency maps, which required insertion angle measurements to be undertaken prior to determining the frequency allocation. Thirdly, the possibility of adjusting frequency allocation based on pitch perception ability in different areas of the cochlea was investigated. The results of the experiments offered new information in the areas of acclimatisation, performance with different frequency allocations and electrode discrimination in different areas of the cochlea.

A new strategy for selecting frequency allocation was developed, based on pitch perception ability for different electrode pairs. For participants in the experiment, implementation of the new strategy would have resulted in the improved performance on a sentence test for some participants, whilst others were not disadvantaged. The new strategy is detailed in Chapter 6.

Chapter 2: Introduction

2.1 Pitch Perception

Pitch is defined by the American National Standards Institute (1973) as 'that attribute of auditory sensation in terms of which sounds may be ordered on a scale extending from low to high. Pitch depends mainly on the frequency content of the sound stimulus, but it also depends on the sound pressure and the waveform of the stimulus.' Pitch cues contribute to the perception of both speech and music. For CI users, speech in quiet may be understood reasonably well when pitch cues are severely degraded (Shannon *et al.*, 1995), but in noise and in difficult listening environments, pitch perception is important for speech perception (Wilson and Dorman, 2008). In relation to music, rhythm can be perceived without pitch cues but pitch perception is necessary to appreciate melody.

The pitch sensation which is elicited when a cochlear implant (CI) electrode is stimulated is determined by a number of different factors. Firstly, the position of the electrode: electrodes near the base of the cochlea typically produce a high-pitched sensation whilst those near the apex give a low-pitched percept (Clark *et al.*, 1981). Secondly, the function of neural tissue in the region of current spread from the electrode within the cochlea affects the perceived pitch (Baumann *et al.*, 2011). For example, if an electrode is situated in an area where few spiral ganglion cells are present, take-up of the stimulation in the area adjacent to the electrode may be poor, and current may need to spread over a wider area for the sound to be perceived, giving a different place-pitch sensation. Thirdly, amplitude modulations, which are present in signals presented by the implant, can make a contribution to pitch if they have modulation frequencies which do not exceed approximately 300 Hz (Loizou, 1998). This is a 'temporal' pitch cue and may be more salient for frequencies in the middle of this range (see for example, Kreft *et al.* (2010) and Luo *et al.* (2008)). Fourthly, CI recipients generally adapt to the pitch of speech sounds presented by the implant over a period of time (Reiss *et al.*, 2007), and the extent to which they have done this affects the perceived pitch, a process known as acclimatisation. CI users can experience sensations of pitch from low to high (Vermeire *et al.*, 2008), corresponding approximately to the speech frequency range.

The four contributory factors to pitch perception mentioned above are somewhat independent of the CI stimulation parameters. CI stimulation parameters can also affect the pitch percept for individual CI recipients. One of these is the frequency-to-electrode allocation. The frequencies assigned to individual electrodes can be adjusted in a cochlear implant, although this is not often recommended by CI manufacturers and the extent to which it can be done varies between devices. However, as there are a number of different contributions to pitch perception, and these vary between individuals, it is not certain that using the same frequency allocation for all CI users with a particular device will result in optimal performance. This study is concerned with testing this hypothesis. If the default frequency allocation is not ideal for all CI users, there is a need to identify alternative allocations which will result in improved performance, either for an individual or a group of individuals. There is also a need to predict which allocation will offer the best performance for an individual recipient.

2.1.1 Place Pitch

For normal-hearing listeners, there are two mechanisms of pitch perception. The place-pitch percept relates to the place of maximum excitation of the basilar membrane for an incoming sound of a given frequency. It has been described by the Greenwood function (Greenwood, 1990): the frequency F (Hz) at a given position x is given by the following equation:

Equation 1 The Greenwood Function

$F=A(10^{ax} - k)$

where A=165.4, a=2.1, k=0.88

The function can be expressed as a function of cochlear length in mm or as a proportion of cochlear length as in Equation 1 and Figure 1.

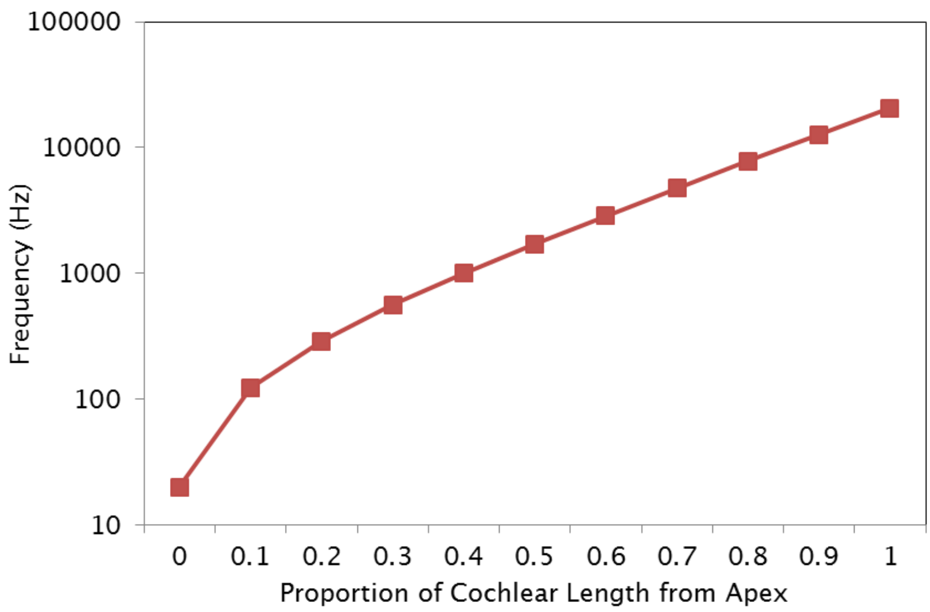


Figure 1 The Greenwood function: Frequency-Position Function of the Normal Human Cochlea as a Proportion of Cochlear Length

2.1.2 Temporal pitch

The second pitch percept available to normal-hearing listeners is the 'temporal' pitch percept, which is described by the 'phase-locking' theory, where pitch is represented by the timing of action potentials or spikes in the auditory nerve (Oxenham, 2008). The firing rates of neurons are determined by the frequency of the incoming sound signal, as the intervals between spikes are likely to be multiples of the period of the waveform for a sinusoid. This gives a second cue for pitch perception, which will be called the temporal pitch cue in this document.

2.1.3 Pitch perception for CI users

The individual auditory nerve fibres of CI users may fire at each cycle of a stimulus, producing a temporal pitch cue (Loizou, 1998). However, this mechanism of pitch perception is only effective up to approximately 300 Hz in CI recipients (Shannon, 1983).

By contrast, the place-pitch cue is effective across the speech frequency range and has been utilised to good effect by CI users since the introduction of multi-channel cochlear implants in the 1980s. Its use has led to increased understanding of speech and improved listening experiences for CI users, when compared with what was possible with single channel implants (Wilson and Dorman, 2008a).

CIs generally filter incoming sounds into a number of contiguous frequency bands (Oxenham, 2008). They extract the temporal envelope in each band and present charge-balanced, biphasic pulses at a fixed rate to the electrodes. Pulses are amplitude-modulated by the temporal envelope of each band and the frequencies assigned to each electrode follow the tonotopic order of the cochlea, approximately.

2.2 The Impaired Cochlea and Pitch Perception

2.2.1 Function of Neural Tissue in the Region of Current Spread from CI electrodes

Whilst hair cells are the route by which normal-hearing listeners access the auditory nerve, this is not necessarily the case for CI users. A histopathological study by Fayad and Linthicum (2006) showed that hair cells and peripheral processes were not necessary for a successful CI outcome. In a series of 14 implanted temporal bones, they found that hair cells were only present in one case and peripheral processes were only present in four. The two best performers had no remaining dendrites/peripheral processes in any cochlear turns, leading to the conclusion that CI users access sound via stimulation of spiral ganglion (SG) cells. It has been found that there is a relationship between the density of SG cells and the slope of the function relating stimulation level to the magnitude of the electrically-evoked Compound Action Potential (Pfingst *et al.*, 2015) in animal studies. This suggests that the performance of CI recipients will be dependent on the health of the implanted cochlea.

2.2.2 Relative Positions of Hair Cells and SG Cells

SG cells are not positioned in the same locations in the cochlea as hair cells. They are positioned in the modiolus, in Rosenthal's canal, whereas hair cells are located along the length of the basilar membrane, which is part of the organ of Corti. The mean length of the SG (13.7 mm) was found to be much shorter than the mean length of the basilar membrane (33.1 mm) in a study by Stakhovskaya *et al.* (2007). The SG extends over approximately 1.75 turns whilst the OC extends over approximately 2.75 turns (Kalkman *et al.*, 2014). In addition, Stahkovskaya *et al.* found that the relative spacing of cells along the length of the OC was different from the relative spacing of cells along the SG, for cells corresponding to the same frequencies. In a study by the same group (Sridhar *et al.*, 2006), a mathematical function was derived, which describes the difference in cochlear location for frequency-matched hair cells (positioned along the OC) and SG cells. It was found that the relationship between them could be expressed as shown in Figure 2 and equation 2.

Equation 2 Relationship between the position of frequency-matched hair cells and SG cells by Sridhar *et al.*

$y= -5.7E\text{-}05x^3 + 0.0014x^2 + 1.43x$

where y= % distance from the base for SG cells and x= % distance from the base for the OC

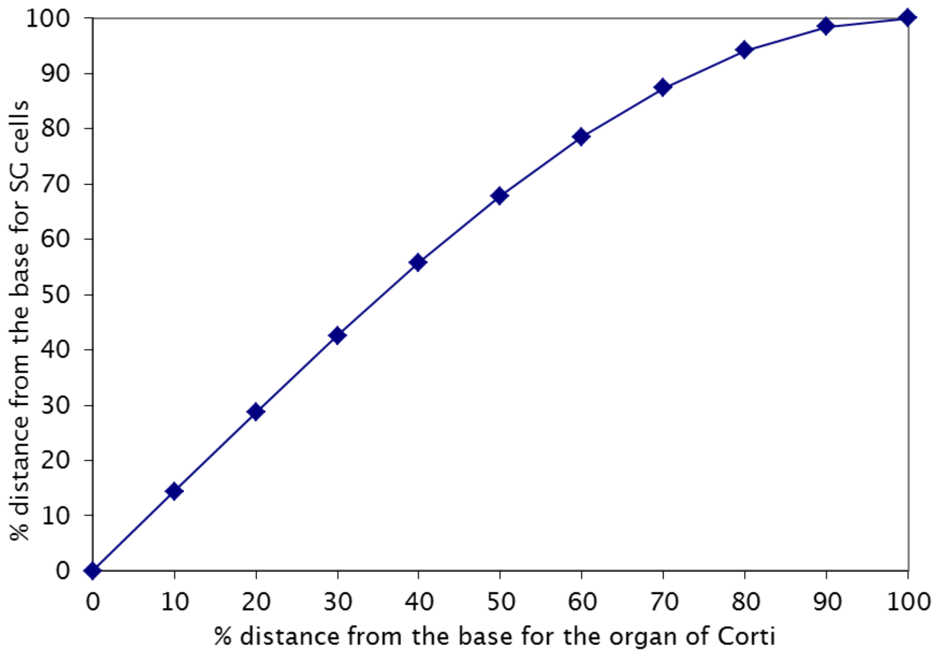


Figure 2 Relationship between position of frequency-matched hair cells and SG cells

Whilst Greenwood's function indicates that hair cells are uniformly spaced along the length of the OC, this function indicates that SG cells are also relatively uniformly spaced in the basal turn, but thereafter SG cells are more closely spaced, especially towards the end of the SG in the middle turn of the cochlea. Sridhar *et al.* found that along the OC, critical bands corresponded to a distance of 0.95 mm. This corresponds to the area over which one sound will interfere with the perception of a second sound for a normal-hearing listener. However, critical band distance along the SG varied from approximately 0.6 mm near the base to 0.32 mm in the lower middle turn.

The same group (Stakhovskaya *et al.*, 2007) described the relationship between percentage length of the OC and percentage length of the SG mathematically, as a function of angle from the base; these are plotted in Figure 3. When equation 2 is applied to the percentage length of the OC, it is possible to see that this gives a very similar result to the % length of the SG as a function of angle from the base, as expected.

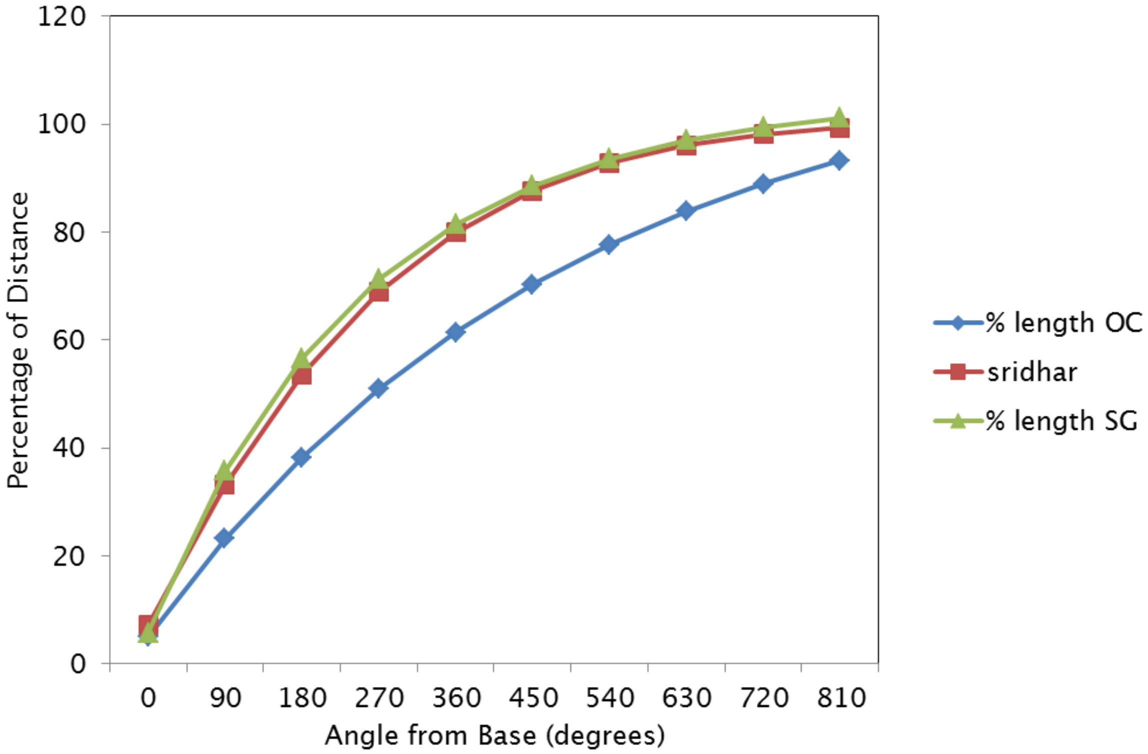


Figure 3 Distance along the OC and along the SG as a function of angle from the base of the cochlea. The Sridhar curve in red represents equation 2 applied to the % length of the OC.

Interestingly, the basal turn of the cochlea, which corresponds to approximately 60% of the length of the OC, accounts for approximately 80% of the length of the SG (Sridhar *et al.*, 2006). The remaining 20% of the SG is found over the next 29% of the OC. The last 11% of the OC contains no SG on average (Sridhar *et al.*, 2006). This suggests that there may be no additional benefit to stimulating a CI beyond this point, especially for those lacking peripheral processes.

Stakhovskaya *et al.* (2007) went on to compare anticipated frequencies for different angles of insertion along the OC and SG. The mean results are shown in Figure 4. These are plotted alongside similar data for the OC, which has been calculated by applying equation 1 to similar data from a cochlear modelling study by Kawano *et al.* (1996).

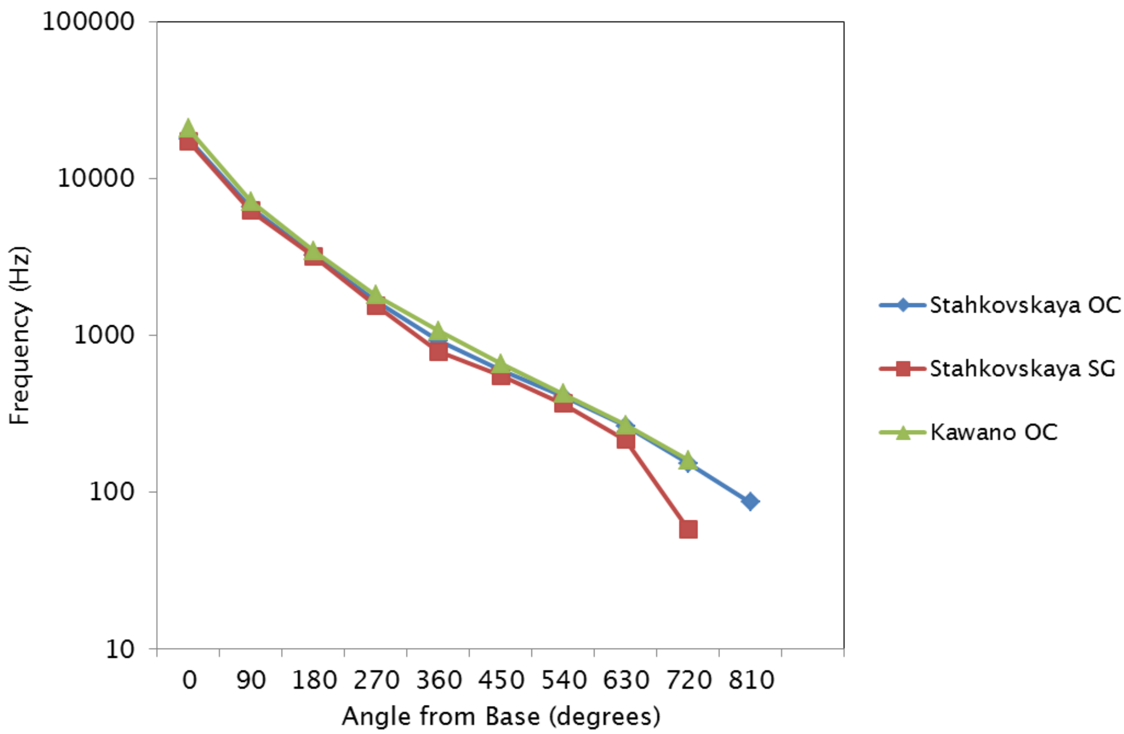


Figure 4 Frequency matched points for the OC and SG from Stakhovskaya *et al.* (2007) and calculated for Kawano *et al.* (1996)

The frequency matched points given by Stakhovskaya *et al.* (2007) for the SG are not very different from those for the OC. However, they do differ for angles beyond 630˚, which corresponds to the end of the SG in the study by Kalkman *et al.* (2014). The results from the Kawano and Stahkovskaya studies for the OC are similar for most angles but deviate to some extent around the 360˚ point.

The above studies predict the mean frequencies perceived by CI users for different insertion angles, based on the anatomy of the cochlea. They do not take the likely current spread from CI electrodes into consideration. A modelling study by Saba *et al.* (2014) suggests that current spread is broad for electrodes using monopolar stimulation and is also dependent on the position of each electrode relative to the modiolus. For lateral wall electrodes, using monopolar stimulation, the model predicts that the resulting voltage at the SG is a broad peak, which falls to half the peak level more than one mm from the peak in either direction, for a realistic input current of 125 μA. The mean length of the SG in Stahkovskaya *et al.*'s study was <14 mm. This suggests that whilst the frequency-position function of the cochlea may be predicted for normal-hearing individuals and for CI users from anatomical studies, the pitch-percept available to CI users is likely to be much less precise than the frequencies given in the study by Stahkovskaya *et al.* might suggest.

Another group have developed a computational model of the implanted human cochlea, which takes into consideration the anatomy of the cochlea and electrical potentials developed by CI electrodes (Kalkman *et al.*, 2014). The model predicts place-pitch for given insertion angles, for electrodes which are located medially or laterally (further details of electrode location are given in section 2.3.1), and for cochleae where peripheral processes are intact and for those where peripheral processes are degenerated. In all cases, it suggests that a range of frequencies are perceived when an electrode is stimulated. The frequency range excited is broader for electrodes with an insertion angle greater than 540˚, than for electrodes with an insertion angle of less than this. In cases where peripheral processes are degenerated, stimulation beyond 540˚ results in the same neurons being excited, regardless of the position of the electrode. Hence it suggests that no further changes in place-pitch percept are possible beyond this point. However, in cases where peripheral processes are intact, a narrower area of excitation may be stimulated beyond 540˚, suggesting that for some CI users, differences in the place-pitch percept are feasible beyond this point. The model predicts that the area of the cochlea stimulated by a lateral wall electrode at 540˚ corresponds to characteristic frequencies between approximately 100 and 400 Hz, which is both larger and lower than the expected range of frequencies based purely on variations in anatomy: for the OC at this point, the expected frequency range is from 331 to 462 Hz and for the SG, the range is from 283 to 400 Hz (Stakhovskaya *et al.*, 2007).

2.3 CI Electrode Arrays

2.3.1 Position of the Inserted Electrodes

CI electrode arrays vary in length and in the position which they adopt in the cochlea once inserted. Some electrode arrays are designed to adopt a peri-modiolar position, such as the Nucleus Contour Advance and Advanced Bionics Helix arrays, whilst others follow the course of the lateral wall, such as the MED-EL standard, MED-EL Flex28, the Advanced Bionics 1J and the Nucleus CI522 electrode array. The MED-EL standard array is 31.5 mm whereas the Nucleus CI522 (slim straight) electrode array can be inserted to either 20 or 25 mm, even though these are both lateral wall arrays. Differences in electrode array length give rise to considerable variation in insertion angles, resulting in a situation where some implant recipients are likely to receive a deeper sensation from the stimulation of apical electrodes than others.

As expected, longer electrode arrays give larger insertion angles than shorter electrode arrays: in a study with ten temporal bones (Franke-Trieger *et al.*, 2014), the MED-EL 20 mm array yielded a mean insertion angle of 341˚, whilst the 31.5 mm array yielded a mean insertion angle of 673˚.

Insertion angles also vary considerably between individual recipients, even for those implanted with the same device (van der Marel *et al.*, 2014). This is unsurprising, given the fact that cochleae vary considerably in size and shape, even for those with normal morphology. Cochlear length was found to vary between 28.0 and 40.1 mm in a study of fifty men by Ulehlova *et al.* (1987). Insertion angles varied between 540˚ and 720˚ for full insertions in a temporal bone study with the MED-EL standard array by (Radeloff *et al.*, 2008). Furthermore, the pathology giving rise to the deafness may cause obstructions in the cochlea (e.g. in the case of ossification following meningitis) and this can limit the extent to which the implant can be inserted and only a partial insertion is achieved. Even in cases of normal cochlear morphology a full insertion of the electrode array is not always achieved.

However, whilst some variability is due to variations in cochlear size, van der Marel *et al.* (2014) found that a substantial amount of the variance was due to differences of insertion. In a study of 336 patients, analysis of pre- and post-operative CT scans showed that 13% of the variation in insertion angles for AB devices was explained by variations in cochlear size; 81% of the variance was explained by the combined effect of size and surgical insertion. Differences of mean insertion angle can also be found between different studies with electrodes of the same length. For example, the mean insertion angle for eight participants with the MED-EL Flex soft electrode array in a study by Vermeire *et al.* (2008) was 653˚ (excluding S12 for whom E1 had a smaller insertion angle than E2), compared with 544˚ for participants with the MED-EL standard electrode array in a study by Landsberger *et al.* (2015). Similarly, the position of the most basal electrode varies between studies. Whilst the mean insertion angle for the most basal electrode in the Vermeire study was 42˚, it was only 10˚ for the Landsberger study. Some of this variation (approximately 10˚) may be attributed to different measurement techniques, and will be discussed further in section 2.5.2, but a larger proportion is likely to be due to different surgical techniques. Mean insertion angles for individual electrodes from three different studies are shown in Figure 5 (Dorman *et al.*, 2007, Landsberger *et al.*, 2015, and Vermeire *et al.*, 2008).

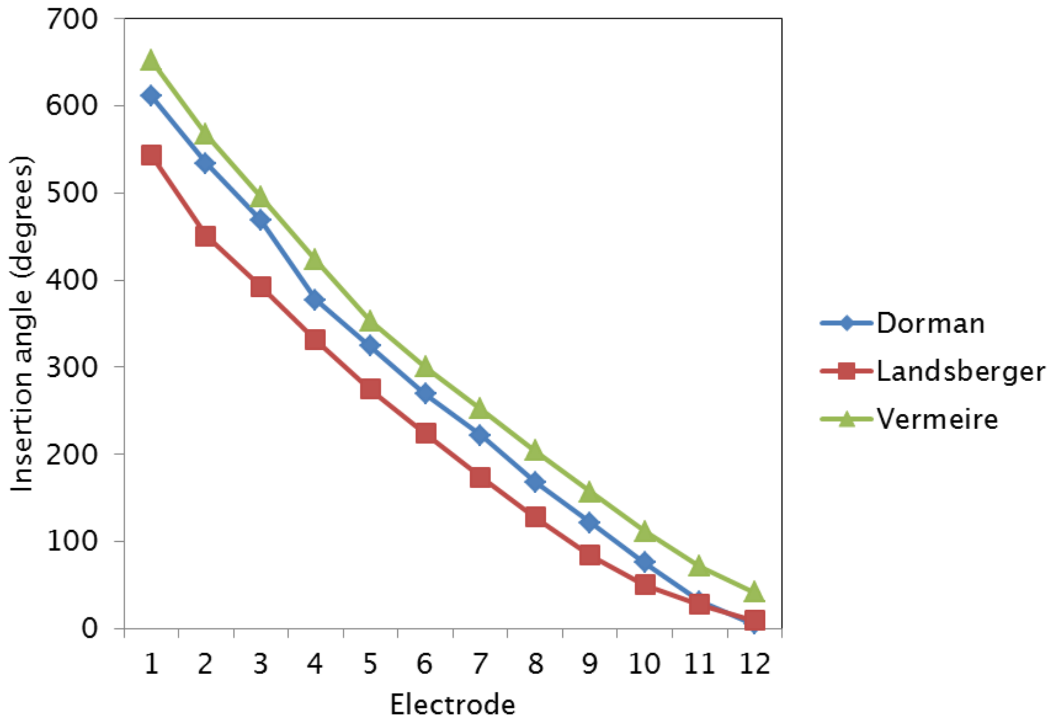


Figure 5 Mean insertion angles for individual electrodes for three studies using long MED-EL electrode arrays

2.3.2 Number of Electrodes and Position Relative to the Modiolus

The number of active electrodes also varies between different electrode arrays. All the currently available MED-EL electrode arrays have 12 active electrodes, whereas the current Advanced Bionics electrode arrays have 16 active electrodes and the current Nucleus electrode arrays have 22 active electrodes. As the shorter arrays also have more electrodes, electrode spacing is considerably smaller for the shorter electrode arrays.

Differences in the number of active electrodes and the position of the array relative to the modiolus are likely to affect current spread and therefore may affect frequency resolution. A modelling study by Saba *et al.* (2014) suggests that placement near to the modiolus may offer more focussed stimulation when compared to lateral wall placement, which could give an improved place-pitch percept.

Placement of the electrode array closer to the modiolus was found to improve speech perception in a large study of CI outcomes (Holden *et al.*, 2013). A possible explanation for this finding, suggested by the authors, is that greater angular distances were covered by electrodes closer to the modiolus and this might have improved frequency resolution. However, only those electrode arrays which were entirely located within the scala tympani were included in this analysis; placement of electrodes in the scala vestibuli was found to be negatively correlated with outcomes and this was found to be more likely with modiolar hugging electrode arrays (Holden *et al*., 2013, Wanna *et al*., 2014).

It might be anticipated that a larger number of active electrodes would offer more opportunities for precise pitch perception and offer better performance. However, studies investigating the number of active electrodes on performance show that this is only true to a limited extent: Wilson and Dorman (2008b) suggest that whilst CIs may have as many as 22 active electrodes, at the time of writing only four to eight effective sites of stimulation were supported by current designs.

2.4 CI Parameters

2.4.1 Mode of Stimulation and Current Spread

Monopolar stimulation is the default mode of stimulation for CIs currently and recently manufactured by Advanced Bionics, Nucleus and MED-EL. Spread of electrical current from individual electrodes is broad in this mode (Saba *et al*., 2014). In the past, some CI systems offered other stimulation modes as their default mode of stimulation. The Nucleus 22 system (which was current until 1996) was able to deliver stimulation in bipolar, common ground or pseudomonopolar mode and hence both active and reference electrodes were always in the cochlea. Bipolar stimulation typically gives a narrower spread of electrical stimulation than monopolar stimulation (Pfingst *et al*., 2001) and frequencies assigned to electrodes programmed in a bipolar stimulation mode may be perceived over a smaller area of the cochlea than those programmed in monopolar mode.

2.4.2 Type of Stimulation and Rate

CI systems deliver charge-balanced, biphasic pulses to the cochlea in most cases. The pulses may be delivered at a fixed rate e.g. 900 pulses per second per channel, as in the Nucleus system, or at a rate determined by the incoming sound signal. The type of stimulation (fixed rate or variable, sequential or simultaneous) is determined by the processing strategy implemented in the device. Most strategies, which are available in current devices, have been developed from or have some similarities with the Continuous Interleaved Sampling (CIS) strategy, developed by Wilson and others (Wilson *et al.*, 1991). The CIS strategy uses fixed rate sequential stimulation, with each available electrode being stimulated at the same high stimulation rate (generally 1000 pulses per second per channel or greater). The ACE strategy offered in Nucleus devices selects a limited number of channels for stimulation in each stimulation cycle but still uses fixed rate sequential stimulation.

As mentioned previously, there is a limited temporal pitch cue available from information in the amplitude envelope. If frequency allocation experiments are undertaken and the lower boundary of the frequency range is unchanged, the change of frequency allocation will have no effect on any temporal pitch cues. If the frequency range is reduced at the low frequency end, there may be some loss of pitch information from the loss of this cue. In addition, an extension of the temporal cue available in MED-EL devices was introduced fairly recently (Krenmayr *et al.*, 2011). In the MED-EL 'fine structure' (FS) processing strategies, zero crossings trigger a sequence of stimulation pulses on apical electrodes in order to present the instantaneous within-channel frequency. With the FSP (Fine Structure Processing) strategy, the number of channels which have this additional frequency cue depends on a number of stimulation parameters including the frequency range. With the FS4 and FS4-p strategies, the number of channels with this additional cue is set to four. With the FS4-p strategy, the pulses on these channels are no longer sequential; there is some parallel stimulation on the fine structure channels. Some studies report differences in performance for pitch-related tasks between different strategies (e.g. Simonyan, 2012). With the FSP strategy, the number of channels which have this additional frequency cue depends on a number of stimulation parameters including the frequency range, and is between zero and four. Hence, the presence or absence of this 'fine structure' cue should be considered if MED-EL CI users participate in frequency allocation experiments.

2.4.3 Covariance of CI Stimulation Parameters

In some cases, adjustment of one CI stimulation parameter will affect the setting of another parameter, or two or more parameters. Table 1 gives details of CI parameters and Table 2 and 3 give details of which CI parameters co-vary.

Table 1 CI Stimulation Parameters

Parameter	Description and current default for MED-EL Opus 2 processor
Number of electrodes	Electrodes can be activated or deactivated if necessary; default is for all 12 intra-cochlear electrodes to be activated
Threshold levels	Minimum level of stimulation for each electrode; adjusted for each individual or set to 10%
Maximum Comfort levels	Maximum stimulation level for each electrode; adjusted for each individual to an appropriate level
Strategy	Determines how stimulation will be delivered. Default is FS4; stimulation rate is dependent on incoming sound for channels 1 to 4 but fixed for channels 5 to 12; if FS4-p is used, there will be some parallel stimulation on the fine structure channels. If the strategy is changed to FSP, there will be between zero and four 'fine structure' channels; with HD-CIS, there are no 'fine structure' channels.
Pulse duration	Dependent on MCL; can be set to a minimum value
Rate of stimulation	Dependent on MCL, strategy and pulse width; defaults to the maximum value available but can be reduced
Frequency range	Default is 100 to 8500 Hz; can be adjusted
Frequency allocation spacing	Default is 4^{th} order polynomial function; assigns greater proportion of frequency range to apical channels
Maplaw	Function relating amplitude of signal output to input; with default setting, the amplitude of output increases quickly with signal input at low levels but more slowly above 20% of dynamic range; rarely adjusted.
Automatic Gain Control (AGC)	Compression ratio defaults to 3:1; rarely adjusted
Microphone sensitivity	Default is 75%. Can be adjusted by recipient or clinician

Table 2 Interactions Between Different CI Parameters for the FSP strategy. The first column shows the parameter being adjusted; ticks along the same row indicate other parameters which may be affected.

Parameter	Number of fine structure channels	Rate of stimulation	Frequency range	Frequency allocation spacing
Number of electrodes	✓	✓		✓
Threshold levels				
Maximum Comfort levels	✓	✓		
Pulse duration		✓		
Rate of stimulation				
Frequency range	✓			
Frequency allocation spacing	✓			
Maplaw				
Automatic Gain Control (AGC)				
Microphone sensitivity				

Table 3 Interactions Between Different CI Parameters for the FS4 and FS4-p strategies. The first column shows the parameter being adjusted; ticks along the same row indicate other parameters which may be affected.

Parameter	Number of fine structure channels	Rate of stimulation	Frequency range	Frequency allocation spacing
Number of electrodes				✓
Threshold levels				
Maximum Comfort levels	✓	✓		
Pulse duration		✓		
Rate of stimulation				
Frequency range	✓			
Frequency allocation spacing	✓			
Maplaw				
Automatic Gain Control (AGC)				
Microphone sensitivity				

2.5 Relationship between Pitch Percept and Insertion Depth

2.5.1 Differences in Insertion Depth

As insertion angles vary widely (as discussed in section 2.3.1) and pitch perception is dependent on the place of excitation in the cochlea (as discussed in section 2.1), it follows that the pitch percept associated with stimulation of a specific electrode along the array (e.g. the most apical electrode) will be different for individual recipients. This may be true even amongst those with a full insertion of the same device. However, Landsberger *et al.* (2015) found that differences which were due to varying electrode array lengths, were to some extent offset by differences in the frequency allocation setting between different manufacturers.

The estimated perceived frequencies for the mean electrode insertion angles for the implants which were included in the Vermeire *et al.* (2008) and Landsberger *et al.* (2015) studies are shown in Figure 6. These have been calculated using data from table 2 of a study by Kawano *et al.* (1996), to find an estimate of the proportion of basilar length for each electrode and then the Greenwood function has been applied, as in equation 1. The start of the OC was assumed to be at 10˚ for the participants in the Vermeire study, as a different measurement technique was used (see section 2.5.2 for further details). It is possible to see that for most electrodes, there is an approximately exponential relationship between the electrode number and anticipated frequencies. For the most basal electrodes in the Landsberger study, the anticipated change in pitch between electrodes is smaller. The difference in estimated electrode frequency varies between the two studies by approximately 0.7 octaves, when averaged over electrodes 1 to 11.

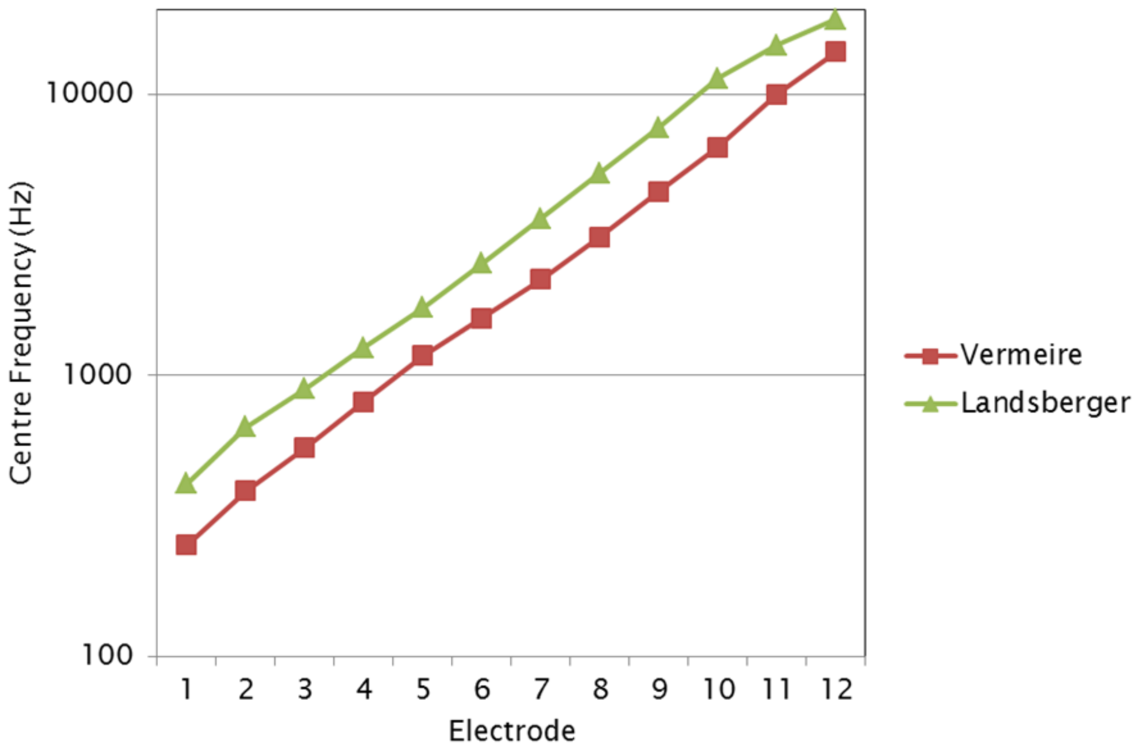


Figure 6 Anticipated Greenwood Frequencies for Electrodes with the Mean Insertion Angles given in the Vermeire *et al.* and Landsberger *et al.* studies

2.5.2 Measurement of Insertion Angle

Measurements of insertion angle from post-operative X-rays are not straightforward, due to the fact that the round window is not visualised on the X-ray. However, the position of the round window can be inferred if the superior semi-circular canal (SSCC) and the vestibule are identified. In some studies, the position of the round window has been taken as the point at which a line joining the SSCC and vestibule crosses the electrode array (see for example Boëx *et al.* (2006)). The centre of the cochlea is found from the curvature of the electrode array, facilitating a measurement of insertion angle. In a study by Dorman *et al.* (2007), the CI recipient had a CT scan and from that a post-operative X-ray was constructed. The participant had a MED-EL standard electrode array inserted via a cochleostomy. The angle between the round window and the most basal electrode was found to be small (5˚), even though the distance between them appears to be approximately 1.5 mm. In the Dorman study, it is possible to see that the position 3.5 mm along the electrode array, which represents the distance between the most basal electrode and the end of the array, represents an insertion angle of approximately 30˚. It is likely that similar (cochleostomy) insertions will give insertion angles between 0 and 30˚ for the same type of electrode array and measurement of insertion angle. It can also be seen, from the morphology, that the relationship between insertion angle and linear insertion depth in this area of the cochlea is non-linear.

However, other studies have used different techniques for measuring insertion angles from post-operative X-rays. Xu *et al*. (2000) and Cohen *et al*. (1996) have developed a co-ordinate system, Cochlear View©, which also depends on visualisation of the SSCC and vestibule. The 0˚ reference line is reported to be approximately 13.5˚ different between Cohen's and Boëx's studies (Verbist *et al*., 2010), with greater angles given by the Cochlear View©. However, the end of the OC, as measured by Kawano *et al*. (1996) is taken as 10˚ from the zero reference line on the Cochlear View©. The distance from the midpoint of the proximal basal turn of the cochlea to the end of the OC was found to be 2.7 mm or 12˚ by Skinner *et al*. (2007). So, when the technique of Boëx *et al*. is used, a 0˚ degree angle is close to the end of the OC, as described by Kawano *et al*. (1996).

Insertion angles for basal electrodes in a study by Vermeire *et al*. (2008) are much greater than those reported by Landsberger *et al*. (2015) and Dorman *et al*. (2007): between 25 and 71˚. They used the Cochlear View© for measuring the angles Xu *et al*. (2000), but it appears that the main difference between the reported angles is due to a different insertion technique. The morphology of images of the electrode arrays shown in the two papers appear to be different.

2.5.3 Pitch Matching Experiments

In order to find the perceived pitch associated with CI electrodes at specific locations in the cochlea, 'pitch-matching' studies have been performed. In these studies, unilaterally implanted CI users with significant residual hearing in their contralateral ear have matched the frequency of a tone presented acoustically to their contralateral ear to the pitch percept associated with stimulation of individual electrodes. This has been reported as a difficult task for some CI users, with a reliable pitch comparison difficult to achieve, due to differences in sound quality between electric and acoustic stimuli (Baumann *et al*., 2011). Lazard et al. (2012) performed a sound quality study in which five CI recipients matched the sound quality of electrical stimulation from their most apical electrode to an acoustic signal presented to their contralateral ear. Recipients matched the stimulation to a complex signal, which was inharmonic in three out of five recipients.

One such study was conducted by Dorman *et al*. (2007) with a single MED-EL CI user with a standard electrode array, as mentioned in section 2.5.2. It was found that pitch estimates were approximately one-half octave lower than the Greenwood function between 15 and 20 mm insertion depth and one octave lower than the Greenwood function between 3 and 13 mm insertion depth. There was an approximately exponential relationship between electrode number and frequency for this recipient but the function flattened off towards the apex and the last three electrodes produced essentially the same pitch sensation (these electrodes had insertion angles of 469, 534 and 612°). The results from this study are shown in Figure 7. It should be noted that the Greenwood function was calculated slightly differently from equation 1: it was calculated as a function of OC length, with the value of 'a' taken as 0.629, as the length of the individual's basilar membrane could be found from the image volume data.

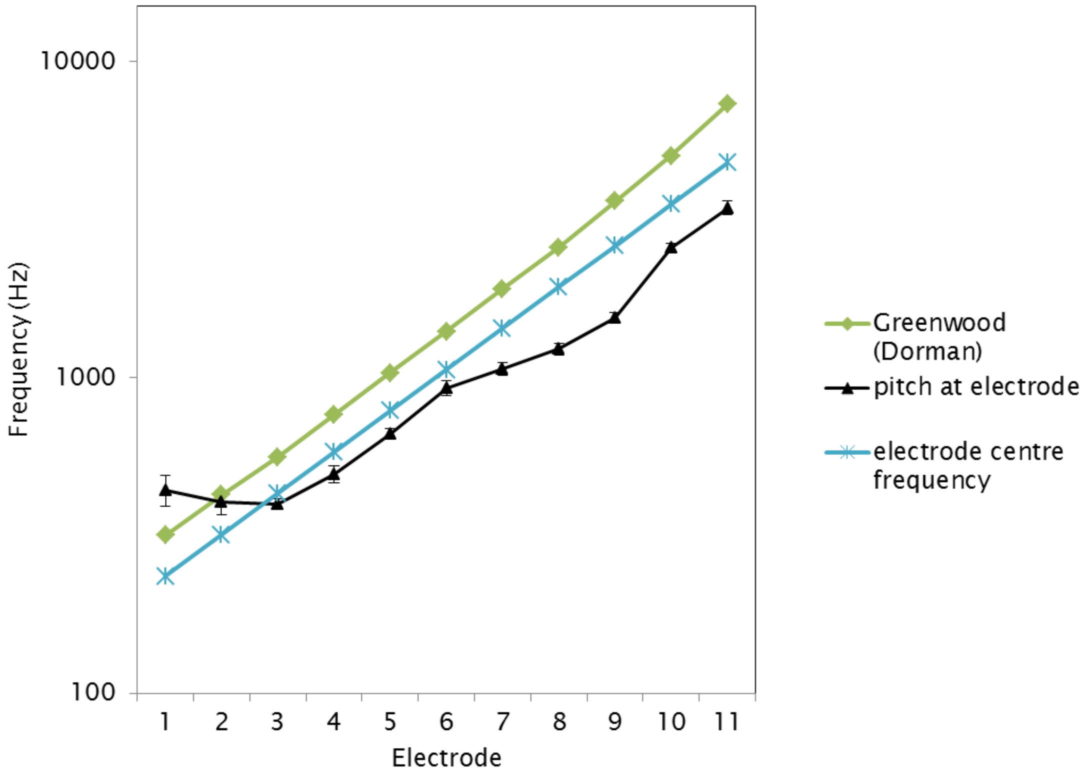


Figure 7 Data from table 4 of Dorman *et al*., (2007), showing results of a pitch matching study with a single participant

Baumann and Nobbe, (2006) performed a pitch-matching study in six users of the MED-EL Combi 40+ device (the same device as in the Dorman *et al*. study), with variable amounts of residual hearing in their contralateral ear. Participants varied in duration of device use but were mostly experienced CI users. Pitch matching was performed for apical to middle electrodes as participants had insufficient hearing to match to higher frequencies. Considerable variability was observed both within and between individual CI users but there appeared to be a more linear relationship between electrode number and pitch percept in their study, rather than the exponential shape expected from the Greenwood function, except that the most apical electrode which did not give a significantly different percept to its neighbour. They commented that the majority of electrodes were matched to a pitch below that predicted from the Greenwood formula.

Boëx *et al.* (2006) performed a pitch matching experiment with six experienced Clarion (Advanced Bionics) CI users. They found that there was an approximately exponential electrode-pitch function for most subjects, as anticipated, but the function flattened off towards the apex in one case. In another case the increase in frequency was less than expected when moving along the array from the apex to the base. They also found that the pitch sensations were about one octave lower than the frequency-position function of a normal ear (the Greenwood function), when insertion angles were used to describe the electrode positions.

Simpson *et al.* (2009) performed a pitch matching experiment with five Nucleus CI users before the implant was tuned. It was found that the estimated pitch-matched frequency for electrode 22 (the most apical one) varied between 579 and 887 Hz for these five participants; the default frequency map for this device has a centre frequency of 250 Hz for this electrode. This suggests that these CI users experienced basal shift when the default frequency map was used and would have found the sound quality high pitched. Surprisingly perhaps, there were no significant differences in speech perception scores when these implant users used a pitch-matched map instead of the conventional map, but the study was limited by the small number of subjects and the fact that all participants in the study also used a contralateral hearing aid, which may have influenced the speech perception test results.

Vermeire *et al.* (2008) performed a pitch matching study with 14 CI recipients who were implanted to suppress unilateral tinnitus and had normal or near normal hearing in their contralateral ears. Participants had a range of experience with the device; on average, testing was performed 11 months post-operatively. It was found that the sensation produced when electrodes were stimulated in different parts of the cochlea approximated the Greenwood function in nine subjects with monotonic pitch functions and near normal hearing in the contralateral ear. In four subjects who did not have monotonic functions, there was a deviation from the Greenwood function of -0.55 octaves on average. The deviation was greatest at the basal end of the cochlea. Interestingly, no effect of duration of implant use was observed. They concluded that, on average, the place-pitch function for CI users does not differ significantly from the Greenwood function.

Carlyon *et al.* (2010) performed a pitch matching study with four AB CI users who were tested prior to the initial tuning of the implant and after acclimatisation. They investigated potential biases in pitch matching procedures which may affect the results. They found that the results were dependent on the frequency range tested and on the starting frequency used in some trials. Once these effects had been controlled for, results did not deviate consistently from the Greenwood function. Additionally, no consistent change in perceived pitch was found after use of the device at different time intervals.

Di Nardo *et al.* (2010) used a different approach when they assessed the electrode-pitch function in seven post-lingually deaf adult CI users with some hearing in their contralateral ear. All had used a CI for at least six months. They compared the pitch of the electrode with the implant's frequency allocation rather than the Greenwood function. It was found that there was a considerable degree of mismatch between the frequencies allocated to each electrode by the implant and the perceived frequency of the electrode when stimulated and compared with a pure tone. The amount of mismatch varied considerably between participants but was correlated with speech perception performance. It is uncertain whether the cases of greater frequency mismatch were symptomatic of a general loss of pitch sensitivity and corresponding difficulty in pitch matching, or due to localised changes in the frequency-position function of the cochleae.

Prentiss *et al.* (2014) performed pitch matching procedures for an implanted ear, with a CI recipient who retained a substantial amount of acoustic hearing following surgery. They found that the perceived pitch of apical electrodes was affected by the rate of stimulation of the electrical pulses. They reported reasonable agreement with the Greenwood function; the participant had a relatively deep insertion.

Plant *et al.* (2014) investigated the pitch percept for the most apical electrode and the change in electrical pitch along the electrode array. They compared these to the SG map described by Stakhovskaya *et al.*, (2007) over the first year of CI use. Care was taken to check that the results were unlikely to be affected by non-sensory bias, following Carlyon *et al.*'s warning. They found that there was considerable variability in the results between the 25 participants included in the study. Whilst for approximately half the participants the initial pitch percept on the most apical electrode was within the frequency range of the filter for that electrode (188 to 313 Hz), significantly below the Stahkovskaya SG map, in the remaining cases it was not. In five participants, the pitch percept dropped over time, but for six others it did not. They also found that the slope of the electrical pitch function was shallower than expected. The initial slope of the electrical pitch function, prior to implant use, was only 0.37 of the slope of the SG frequency-position function. Most participants showed little change in slope over time.

Reiss *et al.* (2015) observed different patterns of pitch perception over time in different bimodal CI users, with some individuals showing acclimatisation to the implant's frequency allocation. Other individuals showed a drop in pitch across the frequency range towards the pitch of the most apical electrode, whilst some showed no change in perceived pitch over time for any electrode.

Zeng *et al.* (2014) found that the frequency-electrode function was one to two octaves below the Greenwood function and also that it was compressed in frequency range, especially for low stimulation rates for three CI users with acoustic hearing in their contralateral ear. In addition, they measured frequency difference limens for normal-hearing controls and CI users using a 2AFC test with acoustic stimuli. They found that electric frequency discrimination was on average 24 times worse than for normal-hearing controls.

Overall the literature relating to pitch matching suggests that there is variability in the extent to which the CI frequency map agrees with the Greenwood function between individual recipients. An exponential function relating electrode number to perceived frequency is a reasonable approximation to the group data but there is some flattening out of the function at the apical end for some CI recipients and additionally deviation from an exponential function for some individuals. Frequency compression was also reported in some studies. Results for some participants indicated that the CI frequency map approximated the Greenwood map reasonably well, whilst in other cases it was an octave or more below it. Some of this variability may be due to differences in methodology between studies but it also likely to be related to differences between participants in insertion depths and position of the electrodes, residual hearing, survival of peripheral processes and SG cells, and acclimatisation (Plant *et al.*, 2014).

2.5.4 Relative Pitch Studies

In addition to studies of pitch matching, some studies of relative pitch have been performed with CI users. These procedures do not require the recipient to have contralateral residual hearing as only the pitch of different electrodes is compared. The results of these studies are in broad agreement with pitch matching studies; a review of those published by 2011 can be found in Boyd (2011). One electrode discrimination study offered some additional information relating to deviation from a logarithmic frequency map in some CI users. Nelson *et al.* (1995) looked at pitch ranking ability for different electrodes in 14 users of the Nucleus 22 device with a range of insertion depths from 13 to 24 mm. They found that place pitch sensitivity varied widely between participants. In some cases, place pitch sensitivity was fairly uniform over the length of the electrode array and followed the normal tonotopic order, with low frequencies perceived at the apical end and high frequencies at the basal end. The variation in pitch sensitivity along the array became more uniform as the separation between the electrodes increased from 0.75 mm up to 3 mm. This suggests that whilst the perceived frequency map may be approximately logarithmic for electrode arrays with uniform spacing and lateral wall placement, local variations in pitch sensitivity along the array will occur less often for electrodes with wide spacing, as in the MED-EL standard array, than for electrodes with narrow spacing, as in the Nucleus 22 device.

In all the post-lingually deafened participants (N=12), lower pitch sensations were elicited when apical electrodes were stimulated than when basal electrodes were stimulated. However, pitch sensitivity varied in a non-uniform way in some individuals with some areas of poor sensitivity and some pitch reversals. In one of the pre-lingually deaf participants, very little place pitch sensitivity was observed over the entire electrode array.

2.6 Speech Perception for CI Users

Cochlear implants have been remarkably successful at facilitating speech perception, with many recipients achieving sentence perception scores of greater than 80%, especially in quiet (Wilson and Dorman, 2008a). Performance is somewhat poorer for monosyllabic words (50 to 60% on average), for which no contextual cues are available. In order to look at perception of individual speech sounds, it may be convenient to consider vowel or consonant sounds separately, as they have different acoustic properties.

2.6.1 Vowels

Vowels are speech sounds in which air flows freely through the mouth. The first stage of vowel production involves vibration of the vocal folds; this produces a quasi-periodic complex tone, with more energy for low frequencies than high frequencies (Moore, 2008a). The complex tone is comprised of harmonics, the amplitudes of which are modified by the vocal tract. The vocal tract behaves like a filter, introducing resonances which affect different frequencies. The resonances show as peaks in the frequency spectrum and are known as formants; they are numbered F1 for the first formant, F2 for the second formant and so on. It has been found previously that variations in spectral resolution between individual CI users affect the perception of vowels (see for example (Harnsberger *et al.*, 2001)). Vowels which have similar F1 and/or F2 are more easily confused than those with more widely spaced F1 and F2.

2.6.2 Consonants

Consonants are speech sounds in which the air flow is either interrupted or limited. Consonants are produced when the vocal tract is either narrowed or constricted at some point along its length (Moore, 2008a). Consonants may be voiced or unvoiced and may or may not have recognisable formant frequencies. Some consonant sounds, such as stops, include periods of silence and some have noise-like qualities.

2.6.3 Speech Intelligibility and Band Importance for Cochlear Implants

The most important frequencies for speech perception have been investigated previously and have been described by the Speech Intelligibility Index (SII) (ANSI, 1997) based on experiments with normal-hearing listeners. The most important frequencies for speech perception are given by frequency weightings for third octave bandwidths for different perception tasks, known as band importance functions (BIFs), as shown in Figure 8. Previous studies have found that frequencies at the extreme ends of the speech frequency range only make a small contribution to speech intelligibility, as shown by the BIFs from the SII in Figure 8.

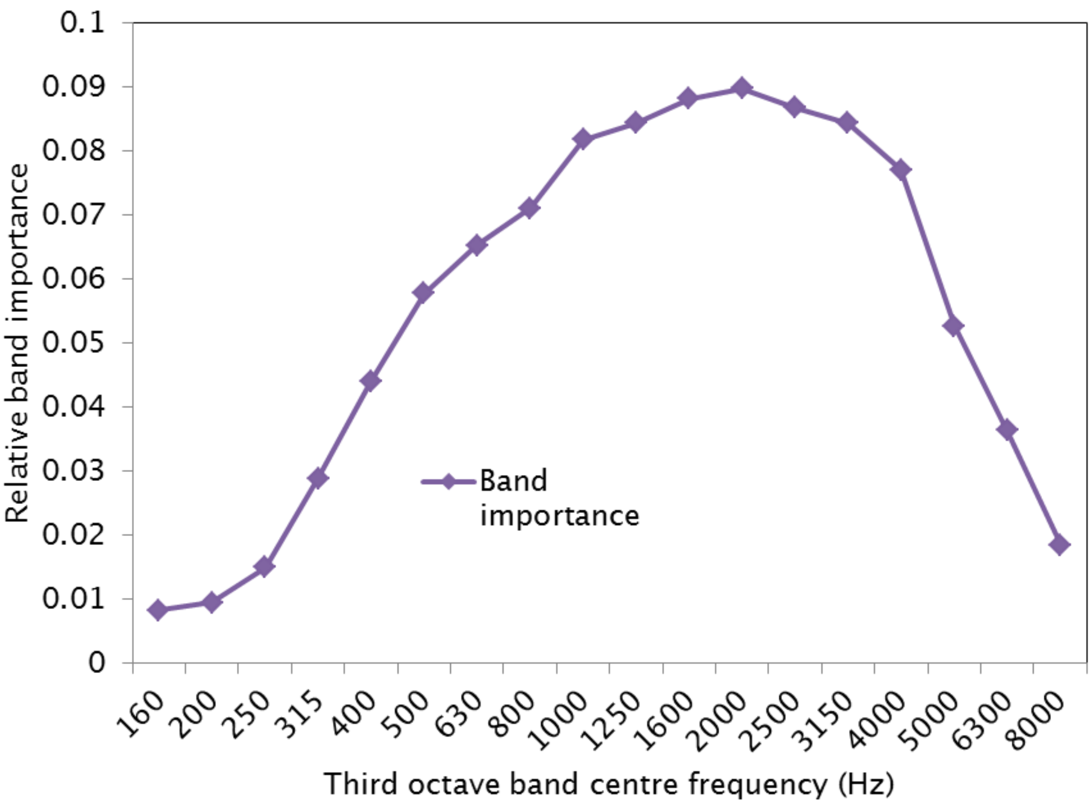


Figure 8 Band Importance Function (BIF) for speech given by the Speech Intelligibility Index

The relative importance of different frequency bands for speech perception has been estimated for CI users in a simulation study with normal-hearing listeners (Whitmal and DeRoy, 2012). It was found that BIFs with a CI simulation are similar to those given in the SII with the exception of a transposition of approximately half an octave, attributed to a difference in the way in which voicing information is perceived. Sounds processed through CIs differ from unprocessed sounds in a number of different ways and, in particular, they lack temporal fine structure and precise harmonic structure. This forces CI users to listen to weaker cues, such as voice onset and formant transitions, to identify voiced consonants, meaning that lower frequency sounds will have greater importance for speech perception than for normal-hearing listeners. The average SII BIFs are shown in Figure 9 along with the same BIFs transposed down half an octave, in line with the findings of Whitmal III and DeRoy's study. In a further study (Whitmal *et al.*, 2015), they found that intelligibility was susceptible to removal or attenuation of frequencies below 1200 Hz, when spectral resolution was reduced. This manifested as a shift in importance. They additionally reported a possible interaction between regions of peak importance and spectral resolution. Reducing spectral resolution in the octave band containing 1400 Hz can reduce intelligibility.

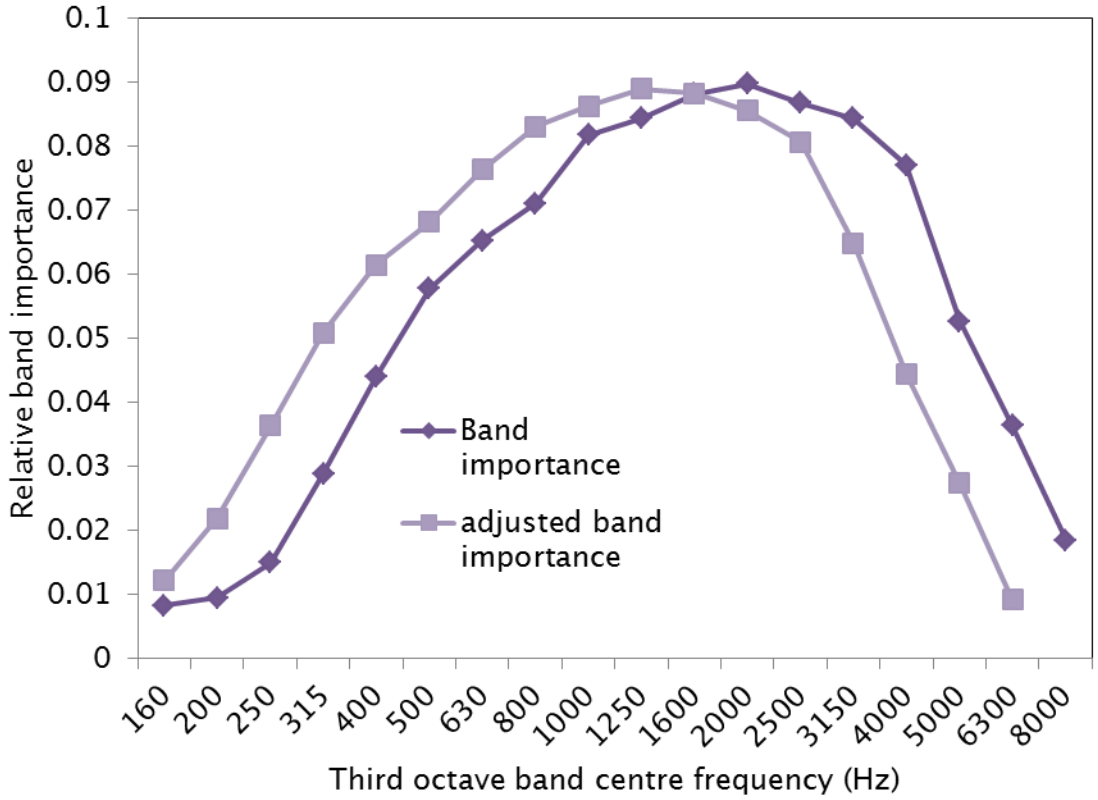


Figure 9 Mean Band Importance Functions for Normal Hearing Listeners from the SII and the same transposed down half an octave as an estimate of the BIFs for Normal-Hearing Listeners with CI Simulations

2.6.4 Speech Perception Assessment

Speech perception can be assessed using a range of different materials such as sentences, words, phonemes, vowels or consonants. A listener is presented with speech from one or more loudspeakers in a sound treated room and asked to repeat what he or she hears or to choose the correct response from a number of choices. Alternatively, speech material may be presented via headphones or live voice. An issue associated with live voice presentation is that it is dependent on the speech of the talker, so recorded material is preferable, as this enables results to be compared between different tests and individuals. Typically, sentences are used to assess an implant user's ability to communicate in everyday situations, whilst other tests assess perception of particular components of speech (e.g. vowel sounds) so that the extent to which an implant user may confuse similar sounds can be considered. Sentences can be tested in background noise to reflect real-world situations or to increase the difficulty of the task. The speech can be presented at a fixed level and scored as a percent correct, or the level of the speech or the noise can be adjusted, based on the listener's responses. In these cases, the score is expressed as a sound level or signal-to-noise ratio (SNR).

2.7 Music Perception for CI Users

Where possible the CI recipient should be given access to the frequency range of music, as many CI recipients also express a desire to listen to music and some are able to do this, even though music does not have the same sound quality through a CI as it does for normal-hearing listeners (Gfeller *et al.*, 2000).

2.7.1 Important Frequencies for Music Perception

The frequency range of music is larger than that of speech and low frequency sounds are of greater importance for music than they are for speech perception. The lowest note on a standard piano has a frequency of just 27.5 Hz whilst tubas and pipe organs have a lowest note of just 16 Hz. Perception of the fundamental frequency (F0) is also more important for music than for speech perception (Looi *et al.*, 2008). However, musical notes for pitched instruments are comprised of the fundamental frequency (1st harmonic) and a number of higher harmonics, the frequencies of which are multiples of the fundamental frequency. The lower harmonics of a complex tone are considered to be the most important in providing the pitch percept and these are resolved by the auditory system in normal-hearing listeners. In the absence of the fundamental frequency, the note still has the same pitch for normal-hearing listeners but will have a difference in timbre, a phenomenon known as the 'missing fundamental'.

At the other end of the frequency range, the highest note on a standard piano has a frequency of 4186 Hz, and so its higher harmonics have very high frequencies indeed. The middle note on the piano, middle C has a fundamental frequency of just 261.6 Hz and harmonics of 523, 785, 1046 Hz etc.

A study of musical frequency range by Snow (1931) found that the sound quality of orchestral music continued to improve as the frequency range was extended downwards to 80 Hz in the low frequencies and upwards to 8000 Hz in the high frequencies. The study involved experienced sound engineers rating the quality of the music as the sound was either low-pass or high-pass filtered. Beyond this range, improvements were less certain. Additionally, frequencies in the middle of the range made a larger contribution to sound quality than those at either end of the range. This suggests a frequency range from 80 to 8000 Hz would be sufficient to give a reasonable sound quality for orchestral music, which is not very different from the speech frequency range discussed in Whitmal III and DeRoy's study (2012).

A more recent study with normal-hearing listeners found that a reduction in the frequency range had an adverse effect on the perceived naturalness of music (Moore and Tan, 2003). In their study, perceived naturalness, which was rated on a scale of one to ten, was highest for music with a frequency range of 55 to 16854 Hz. For speech perception, the naturalness rating was adversely affected if the frequency range was reduced, such that the lower cutoff was higher than 123 Hz or the upper cutoff was reduced from 10869 Hz.

However, a study by Roy *et al.* (2012) found that CI users rated the sound quality of musical sounds similarly, when an unfiltered signal was compared with a high-pass filtered signal with a filter cut-off of 400 Hz, suggesting that low frequency sounds contribute little to the sound quality of music for CI users. The study also suggested that CI users were insensitive to low pass filtering of musical stimuli.

A study by Galvin and Fu (2011) found that melodic contour perception was better for some CI users, for bandpass filtered musical stimuli, covering the middle of the frequency range, than unfiltered stimuli and suggested that this may be due to a reduction in spectral warping, and conflicting temporal and spectral F0 cues. An alternative explanation might be that a greater number of maxima were assigned to the frequency range with the most salient cues in the middle bandpass condition than in the unfiltered condition.

A more recent study by Roy *et al.* (2015) found that CI users rated the sound quality of music differently for different high-pass filter cutoffs, with the highest ratings for the reference (unfiltered) stimuli. Ratings for the HD-CIS strategy were different from those for normal-hearing listeners for high-pass filter settings of 400, 600, 800 and 1000 Hz. They also found a difference for ratings between the HD-CIS and FSP processing strategies and reported ratings closer to those of normal-hearing listeners with the FSP strategy. It is not entirely clear what this might be due to, as the effect was present even for a high-pass filter cutoff of 1000 Hz.

It has been found that people with normal hearing will often have a memory of popular music at the appropriate pitch, as pop songs are commonly heard repeatedly at the same pitch and performed by the same artist (Levitin, 1994). Post-lingually deafened adults, who listened to music prior to losing their hearing, may also be able to recall the pitch of familiar pop songs and notice deviations from the normal pitch.

In summary, the CI frequency range should include important speech frequencies and if possible important frequencies for music. Previous work with CI simulations suggests that the peak in the function of band importance for speech occurs for the third octave bands with centre frequencies of 1250 and 1600 Hz. Frequencies below 100 Hz and above 7000 Hz are unlikely to make a contribution to speech perception in CI users. Frequencies below 55 Hz and above 16000 Hz are unlikely to substantially affect the sound quality of music for normal-hearing listeners; a smaller range might be acceptable for CI users, who have generally shown less sensitivity to a loss of frequency range in the limited number of studies which have been done in this area.

2.7.2 Music Perception Assessment

The method of assessment for music perception is dependent on the type of information that is required. For example, music perception and engagement for CI users has been assessed using questionnaires, which investigate subjective sound quality, music listening and music making preferences (see for example Brockmeier *et al.*, 2007, van Besouw *et al.*, 2011, Driscoll *et al.*, 2015, Gfeller *et al.*, 2000). An alternative method of assessment involves asking the CI user to listen to a series of sound segments and rate these on an appropriate scale. The scale can either be an analogue scale such as a horizontal line representing one extreme of the variable at one end and the other extreme at the other end (e.g. as in Wright and Uchanski (2012) or a scale with a fixed number of points, as in the 100-point scale used in Roy *et al.* (2012). In the CI-MUSHRA method (Roy *et al.*, 2012), samples are rated relative to a reference sample.

Specific aspects of music perception have been assessed using rhythm, timbre, pitch and melody tests: a review of these can be found in Looi *et al.* (2008). Pitch tests investigate either pitch discrimination or the ability to identify if a sound is higher or lower than the preceding one (known as pitch direction or pitch ranking). The intention may be to find a just noticeable difference (JND) for pitch perception for a particular reference note, or to test perception based on percent correct for a number of trials, either within the same frequency range or for different frequency ranges. Melody tests involve longer sequences of notes, but are also tests of pitch perception.

2.7.3 Assessment of Perceived Sound Quality in General

As perceived sound quality is subjective, it is appropriate to assess it using self-rating measures such as questionnaires. Some questionnaires use Likert scales for subjective ratings, such as the Hearing Implant Sound Quality Index (Calvino *et al.*, 2016). Likert scales offer a limited number of choices, exploring the extent to which individuals agree with statements made about a topic and include both positive and negative choices (McLeod, 2016). Other types of questionnaire may offer a greater number of choices, such as the 0 to 100 scale used by the Spatial Hearing Questionnaire (Tyler *et al.*, 2009), and do not typically include negative choices.

2.8 Frequency-to-Electrode Allocation Setting

Adjustment of the frequency-to-electrode allocation or frequency map has been shown to have a marked effect on speech perception (Başkent and Shannon, 2004), at least initially. CIs map low frequencies to the apical end of the array and high frequencies to the basal end of the array, to mimic normal hearing, but there are variations in how this is done between devices, both for the frequency range and in the shape of the function relating electrode number to centre frequency.

2.8.1 Frequency Range

The frequency range delivered to the CI user by the device typically covers the speech frequency range. There are differences between devices, and some devices offer more flexibility to adjust this setting than others. The MED-EL fine structure processing strategies have a default frequency range from 100 to 8500 Hz; the lower frequency boundary is somewhat higher for other devices but the upper frequency boundary is similar for both Advanced Bionics and Nucleus devices.

2.8.2 Shape of the Function

Frequency allocations are typically logarithmic for the upper part of the frequency range but some strategies allocate a larger proportion of the frequency range to the apical electrodes than the basal ones. The default frequency allocation for the MED-EL fine structure processing strategies has a fourth order polynomial function relating the electrode number and lower frequency boundary for each electrode. Default frequency allocation maps for different devices are shown in Figure 10.

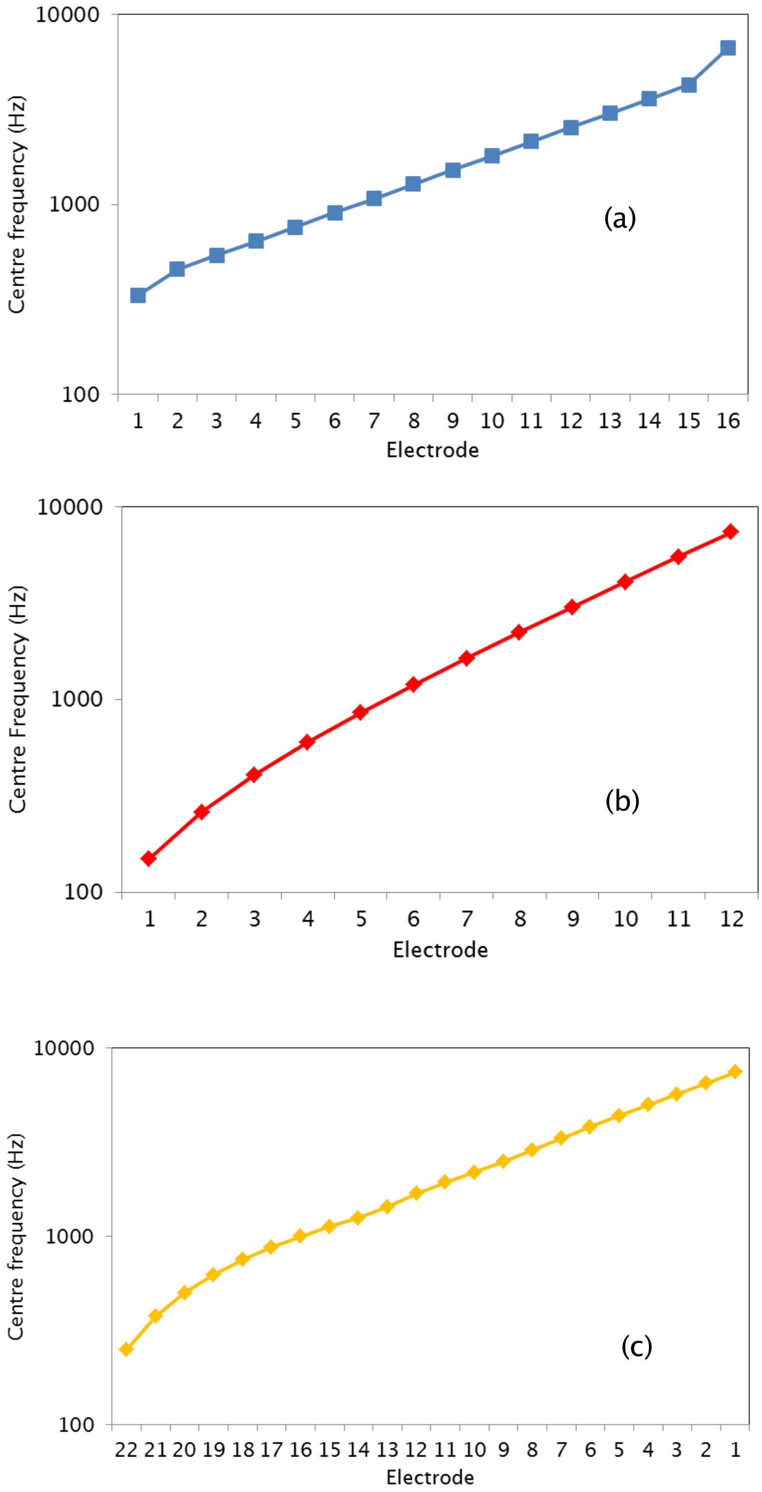


Figure 10 Default frequency allocations for (a) Advanced Bionics HiRes Fidelity120 and Optima strategies (b) MED-EL Fine structure processing strategies and (c) Nucleus ACE processing strategy

2.8.3 Adjustment of the Frequency Allocation Setting

Frequency allocation settings are rarely adjusted for CI users on an individual basis, as manufacturers seldom recommend this, although it is possible for some devices. For the MED-EL fine structure strategy, the frequency range presented to the CI user can be adjusted within the limits of 70 to 8500 Hz and there is considerable flexibility to adjust the allocation to individual electrodes, although this breaks down to some extent if the desired allocation is highly non-uniform. For the Nucleus device, a number of different frequency tables are available and there is also flexibility to adjust frequencies away from the frequency table, by adjusting the number of frequency ‘bins’ assigned to each electrode, so long as frequencies increase from apex to base. For the Advanced Bionics HiRes90k device, only the width of the frequency band assigned to the most apical electrode can be adjusted.

2.8.4 Optimisation of the Frequency Allocation for CI Users

Manufacturers’ default frequency maps follow the Greenwood function to some extent, in that they have logarithmic frequency spacing over a considerable part of the frequency range. However, given the considerable variation in insertion angles between different CI users, it is not possible that all CI users will have their frequency maps aligned to the Greenwood function, which represents the frequency map for normal-hearing individuals. In addition, CI frequency maps do not necessarily follow the same shape as the Greenwood function. For example, the frequency map for the Nucleus ACE strategy and the MED-EL fine structure processing strategies allocates a larger proportion of the frequency range to the apical electrodes, which may maximise the opportunity for perception of temporal pitch cues, as these have been found to be more salient on the apical electrodes (Prentiss *et al.*, 2014). However, pitch matching studies have sometimes reported limited change in place-pitch at the apical end of the array, especially for deeply inserted electrodes (see section 2.5.3). The question arises as to what extent CI users should have their frequency maps aligned with the Greenwood function. Early studies of frequency allocation, which did not measure insertion depth, led Başkent and Shannon, (2005) to suggest that speech recognition is optimised when the frequency information is presented to the normal acoustic tonotopic cochlear location. Studies of frequency allocation with normal-hearing listeners and CI simulations and CI users have focussed mainly on the issues of pitch-matching and compression and expansion of the frequency range.

2.8.4.1 Evidence from Simulation Studies

One of the studies which led to this tentative conclusion was a five channel simulation study with normal-hearing listeners by Dorman *et al.* (1997). They found that speech perception was optimised when the frequencies of sine waves output from each channel of a processor corresponding to the simulated insertion depth (25 mm) were matched to the normal tonotopic frequency, rather than when the simulated insertion depth was reduced to 22, 23, or 24 mm, which produced a basal spectral shift. The effect was particularly noticeable for vowel recognition. Participants in the study had some exposure to CI simulations (12 to 15 hours) prior to the start of the experiment. A further simulation study by Shannon *et al.* (1998) using a four channel vocoder found that speech perception was reduced when frequencies were shifted relative to the matched condition and also when spectral ‘warping’ was introduced by using a log-linear assignment or a linear-log frequency assignment.

Another study using CI simulations, this time with four, eight and sixteen bands, was conducted by Fu and Shannon (1999c). Normal-hearing listeners were exposed to simulations of vowels processed by a CI with and without spectral shift. No exposure to CI simulations was provided prior to the start of the experiment. Performance was good in the matched condition and only dropped by a limited amount when the frequency bandwidth was limited (the apical edge of the frequency allocation varied from 290 to 960 Hz). However, performance dropped off more rapidly when the frequencies of the carrier filter band and analysis frequency bands were shifted relative to one another, resulting in spectral shift. Vowel recognition scores were robust to tonotopic shifts of up to 3 mm (approximately 0.7 octaves) but dropped significantly when spectral information was shifted by more than 4 mm (approximately 0.9 octaves).

In another simulation experiment, this time looking at frequency compression and expansion with four, eight and sixteen channel processors, Başkent and Shannon (2003) found that best performance was consistently observed in conditions where frequency information was matched to its normal acoustic cochlear place. However, some of the alternative allocations did result in a substantial loss of frequency range in this experiment. Based on the results of this and previous studies, they concluded that speech patterns can only tolerate a relatively small degree of distortion in tonotopic space (2 to 3 mm, equivalent to 0.5 to 0.7 octaves).

Subsequent studies have again shown evidence of a matching effect in normal-hearing listeners. Zhou *et al.* (2010) conducted a simulation study looking at the effects of frequency shifts on consonant perception with four, eight, twelve and sixteen channel processors. They found that a spectral shift of 3 mm or more (equivalent to 0.7 octaves) from the normal acoustic map caused performance to decrease significantly. Similarly, Başkent and Shannon (2007) investigated frequency compression and expansion in normal-hearing listeners using eight and sixteen noiseband vocoder processors. One of the conditions tested was a shift only condition and this also demonstrated a matching effect: performance was reduced when the analysis bands and carrier bands were shifted relative to one another.

2.8.4.2 Evidence from Studies Involving CI Users

Fu and Shannon investigated the effect of frequency allocation adjustment in CI users with Nucleus 22 implants and this was reported in one of the studies mentioned above (1999c). A similar effect to that found in normal-hearing listeners was found for CI users in that vowel recognition performance was at its peak over a limited spectral region. This applied when different subsets of electrodes were tested. However, insertion depths varied in the five participants in the study and Fu and Shannon commented that ‘it is unlikely that the peak in the function is determined by the normal acoustic map’ for these five CI users. They observed that best performance occurred at the closest match to the frequency allocation in the recipients’ clinical processor, with which they had at least six months of experience.

Fu and Shannon published the results of two further frequency allocation studies in the same year (Fu and Shannon, 1999a, Fu and Shannon, 1999b). Both studies demonstrated an effect of frequency allocation when vowel recognition was tested. In the 1999a study, five CI users with Nucleus 22 devices and a four channel custom processor with the CIS (Continuous Interleaved Sampling) processing strategy, (more details of which can be found in Wilson *et al.* (1991)), listened to ten different frequency allocations and five sets of four electrode configurations. Vowel recognition was assessed in each condition in an acute study (no time was allowed for acclimatisation prior to testing). In two of the conditions an apical subset of electrodes was compared with a basal subset of electrodes. Performance peaked with different allocations for the apical and basal subsets, and the difference in allocation which produced the best results was equivalent to the distance between the electrode locations (3 mm). They concluded that speech recognition in cochlear implants is highly sensitive to the match between frequency information and electrode location.

In the first part of Fu and Shannon's 1999b study, three Nucleus 22 users were tested with a four channel CIS processor and the electrodes selected for activation were progressively moved in the basal direction. This was an acute study and it resulted in a reduction in performance for vowel and consonant recognition; the effect was larger for vowel recognition.

Başkent and Shannon (2004) looked at frequency-place compression and expansion in CI users. In the first part of this study the effect of frequency shifts were investigated and performance was found to be at a maximum when frequency shifts were minimised, for perception of both vowels and consonants. This was an acute experiment so CI users had no time to adjust to the new maps before their speech perception was assessed.

The simulation studies with normal-hearing listeners which were referred to by Başkent and Shannon (2005) show consistent evidence of a matching effect to the normal acoustic tonotopic place: performance is optimised when frequencies are allocated to their normal acoustic tonotopic place. However, studies with CI users offered more mixed results; speech perception was found to vary as a function of frequency allocation in all of the studies mentioned above, but the frequency map offering best performance did not always correspond to the normal acoustic tonotopic map. Fu and Shannon (1999c) commented that for participants in the 1999c experiment, best performance occurred at the closest match to the recipients' clinical processor rather than to the estimated normal acoustic frequencies. There were also mixed results reported in Başkent and Shannon's 2004 paper for the expansion and compression conditions. Three participants' vowel recognition scores were closer to scores which they predicted from the similarity of the experimental map to the clinical map rather than scores which they predicted from the similarity of the experimental map to the normal acoustic map.

In summary, performance is optimised for normal-hearing listeners in experiments of frequency allocation when the simulation analysis and carrier frequency bands are matched. Frequency shifts away from this matched point result in poorer performance. An effect of frequency allocation is also observed in CI users, but in some participants the best performance occurs when the frequency allocation matches that in the participants' clinical processor to which they have become accustomed.

2.8.4.3 Shape of the Frequency-Allocation Function

If the Greenwood function is used to calculate the frequency map, the band assignment will have approximately logarithmic spacing (see section 2.5.1) for a MED-EL standard electrode array. Whether this will match the perceived frequencies when individual electrodes are stimulated will be depend on the individual. What constitutes distortion for a CI recipient will depend on their individual frequency map.

A simulation study performed by Shannon *et al.* (1998) (also mentioned in section 2.8.4.1), using a four-channel vocoder found that speech perception was reduced when spectral 'warping' was introduced by using a log-linear assignment or a linear-log frequency assignment. However, this may be due to the fact that the most important speech frequencies were allocated to a single channel (Whitmal *et al.*, 2015).

Fu and Shannon conducted an experiment of tonotopic warping with Nucleus 22 users, (Fu and Shannon, 1999b) and found an improvement in vowel recognition and consonant recognition scores when frequencies were allocated to filters using logarithmic frequency spacing, as in the Greenwood function, rather than assigning filters to equal frequency differences. However, only three participants were tested in this study.

Fu and Shannon (2002) also measured phoneme recognition in five Nucleus 22 users with a custom four-channel CIS processor. They systematically varied the analysis bands from logarithmic to linear in six conditions. Performance was best in the logarithmic and near logarithmic conditions. These conditions were also closest to the clinical processor map.

McKay and Henshall (2002) investigated the possibility that selectively increasing the discrimination of sounds below 2600 Hz would improve speech perception. The rationale for this was that a previous study by Henry *et al.* (2000) found that speech perception was correlated to electrode discrimination ability for electrodes allocated to frequencies up to approximately 2600 Hz. McKay and Henshall hypothesised that increasing discrimination up to this point would improve speech perception. In their experiment, improved discrimination was achieved by allocating nine out of ten electrodes to sounds in this range, compared to uniform logarithmic spacing of the entire frequency range from 200 to 10513 Hz. Full electrode maps were also included in the experiment. Seven Nucleus 22 CI users were tested after two weeks take home experience with each map. Performance with nine electrodes allocated to the lower frequencies was equivalent to the full-electrode maps for vowel perception and sentences in noise but worse for consonant perception. Performance with the uniformly-spaced frequency map with ten electrodes was worse for vowel perception and sentences in noise but equivalent to the full electrode maps for consonant perception. They concluded that the optimal number of electrodes may differ for high and low frequency information.

Leigh *et al*. (2004) went on to investigate the hypothesis that speech perception of CI users could be improved by increasing the number of electrodes allocated to frequencies below 2600 Hz in maps using all the available electrodes. Eight users of the Nucleus 22 device participated in the experiment. Vowel perception was better with the experimental map and consonant perception was not significantly different. However, word recognition was worse with the experimental map in contradiction of the vowel and consonant confusion test results. They suggested that further research was needed to investigate the possible effects of narrowing the filter bandwidth for low frequencies.

Fourakis *et al*. (2007) showed that it can be beneficial to consider the relative contribution of different parts of the frequency range to speech perception when allocating frequencies to different electrodes for CI users. In their experiment, eight participants with Nucleus 24 devices used a custom research processor and it was found that performance was better when approximately half or just over half of the electrodes were allocated to the frequency range between 1100 and 3000 Hz. The authors suggested that resolution of frequencies in this range, corresponding to the second vowel formant, is important.

The above studies offer some information relating to the most appropriate shape of the frequency map for CI users but the results are not completely consistent between studies and only a limited number of CI recipients have been tested. In addition, it is difficult to separate the effect of the shape of the frequency map from the effect of pitch shifting.

Di Nardo *et al*. (2008) recommended a more flexible approach to frequency mapping than was available with the Nucleus CI device at the time at which their study was completed. They advocated mapping to the perceived frequencies of the electrodes rather than using uniform logarithmic spacing, as suggested by the Greenwood function. They assessed this idea in a single patient with a Digisonic device, who had contralateral residual hearing. The frequency map was redistributed following pitch matching tasks. The most apical electrode was matched to a higher frequency than the range which was assigned to it by the implant's frequency map. Subsequent remapping resulted in an improvement in consonant discrimination from 33% to 66% correct.

The improvement in speech perception for the CI user tested in Di Nardo *et al.*'s study suggests that individual frequency mapping should be pursued in order to maximise performance for CI users. However, it is not certain that pitch matching procedures could be successfully performed for the majority of adult CI users and would certainly be impractical for young children. A pre-requisite of pitch matching procedures is the presence of residual hearing in the contralateral ear. Not all CI recipients have residual hearing in their contralateral ear or are unilaterally implanted. Additionally, pitch matching procedures require the CI recipient to have an ability to perceive pitch sufficiently well to compare the pitch sensation from the implant with the contralateral acoustic pitch sensation. Some CI users find this difficult as noted by Baumann *et al.* (2011). It would be preferable to find a different method of optimising the frequency allocation which would be suitable for all CI users.

2.8.5 Frequency Range Experiments

Faulkner *et al.* (2003) investigated the possible effect of a loss of low frequency information on speech perception in a simulation study with normal-hearing listeners. They found that speech perception was significantly reduced if the insertion depth was less than or equal to 19 mm and if the map was matched to the normal acoustic frequencies.

Fu and Shannon (1999a) also adjusted the frequency range available to participants in a frequency allocation experiment but this time with Nucleus 22 users. When basal electrodes were selected, the frequency allocation which gave optimal performance on a vowel recognition task had a lowest corner frequency of 753 Hz, suggesting that inclusion of low frequencies is not essential for vowel recognition even though important F1 (first formant) information may be excluded.

Başkent and Shannon (2005) conducted a further study to investigate frequency mapping with simulated shallow insertions with MED-EL Combi 40+ CI users. They observed that vowel recognition with a wide frequency range was significantly poorer than with a reduced frequency range with a more modest amount of compression. Inclusion of the entire frequency range may limit resolution: if a large frequency range is presented to a limited number of electrodes, each electrode has to accommodate a wide frequency bandwidth whereas if a smaller range is presented, then each electrode only needs to accommodate a limited frequency bandwidth. It may be preferable to present a smaller frequency range whilst ensuring that the most important frequencies for speech perception are included. Başkent and Shannon (2005) compared maps with a limited number of electrodes with 'matched' frequencies to maps with the same number of electrodes but with compressed frequency allocations, which covered the whole frequency range from 184 Hz to 8.9 kHz. In both the compressed and matched conditions, performance was poorer than with the normal clinical map. When the simulated insertion depth was very shallow (e.g. 9.6 mm) the compressed map offered better performance but when the insertion depth was only reduced a little from normal (e.g. 24 mm), the matched map offered better performance than the compressed map. This was an acute study and if acclimatisation had been possible, scores with the compressed map might have improved over time, as creating a compressed map resulted in some spectral shift. However, this study does indicate that there is a trade-off to be had between frequency compression combined with spectral shift and loss of frequency range, when the insertion depth is limited.

Başkent and Shannon (2007) also considered the combined effects of frequency compression/expansion and frequency shifting in a simulation experiment with five normal-hearing listeners. Compressed conditions covered a wide frequency range (184 Hz to 11.84 kHz) whilst expanded conditions covered a greatly reduced frequency range (1.17 to 2.86 kHz), with the 'matched' condition being the only intermediate condition. They found that although frequency compression and expansion were detrimental to speech perception when applied in isolation, there were situations in which frequency compression or expansion could compensate to some extent when frequency shifts were applied. This was in agreement with the results of their 2005 experiment. It is not possible to tell to what extent the frequency range affected performance in isolation from other effects as frequency compression and expansion cannot be applied without affecting frequency range, frequency resolution and producing frequency shifts.

Another frequency expansion and compression experiment was conducted with CI users by the same authors (Başkent and Shannon, 2004). Similar results were reported to the simulation study. However, in order to calculate the frequencies for the matched condition, the depth of insertion was assumed from the length of the electrode array, rather than being measured.

Goupell *et al.* (2008) examined the effects of upper-frequency boundary and spectral warping on sentence perception in noise in six normal-hearing listeners using a CI simulation and 7 MED-EL C40+ and Pulsar CI users. The matched condition in this experiment for CI users was to their normal processor map and the experimental conditions resulted in a change to the upper frequency boundary of the map and in some cases a change to the selection of electrodes. The experimental maps resulted in both spectral shifts and compression/expansion. The ‘matched’ map usually produced the best performance but conditions of limited compression or expansion did not give significantly different performance. However, when expansion or compression was equivalent to a reduction or increase of more than two electrodes, then a decrement in performance was observed. This corresponds to an upper frequency boundary shift of 0.77 octaves. On the other hand, they found that the upper frequency boundary could be reduced from 8.5 to 4.9 kHz without any detrimental effect on sentence perception in noise in the matched condition. This corresponded to deactivation of the two most basal electrodes. They also observed that for one participant, the best speech understanding occurred with an upper frequency boundary of 4.9 kHz, with the frequency range allocated to all 12 electrodes instead of the normal 8.5 kHz upper frequency boundary and on average across the entire population the upper frequency boundary of 4.9 kHz appeared to be a slightly better map than the condition with 8.5 kHz. However, the difference was not statistically significant.

Lin and Peng (2009) found that an extended low frequency range produced better performance on lexical tone identification in Mandarin-speaking children with cochlear implants. This is an interesting finding but it is uncertain whether the improvement was due to the additional frequency information or possibly a better frequency-to-place map.

Riss *et al.* (2011) conducted a comparison of the CIS and FSP coding strategies in a cross-over study with 31 participants. The frequency allocation settings for both maps were equal. No difference in performance was observed although other studies had shown an improvement in performance with the FSP map. They concluded that the improvement found in other studies was likely to be due to the extended frequency range of the FSP map (low frequency boundary = 100 Hz; low frequency boundary = 250 Hz for CIS). The extended frequency range might improve performance by giving CI users access to the fundamental frequency of speech. The frequency maps of the FSP and HD-CIS strategies (which are used in the current MED-EL Opus 2 processor) are shown in Figure 11.

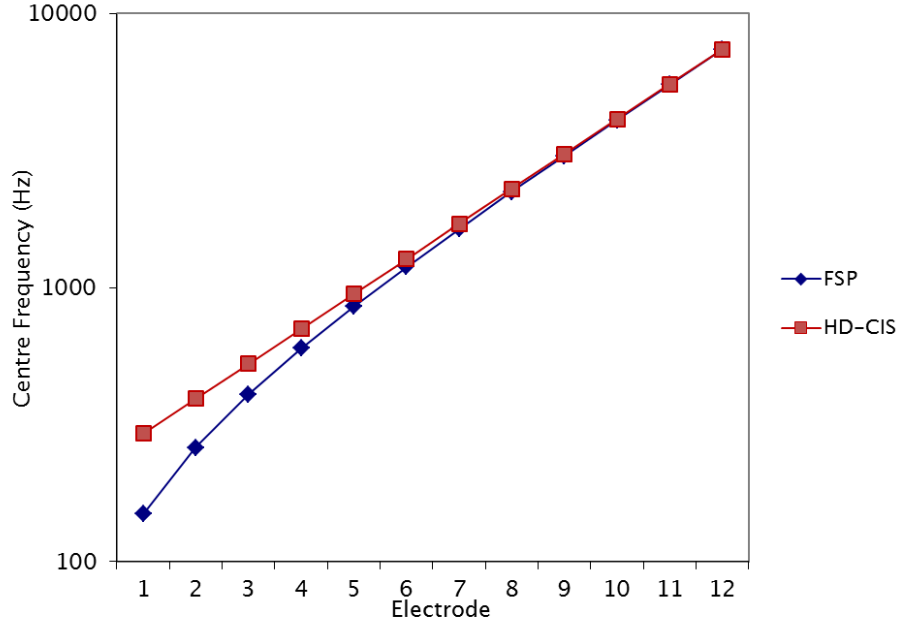


Figure 11 Relationship between electrode and centre frequency for the MED-EL FSP and HD-CIS strategies

In summary, experiments which involve adjustment of the frequency range suggest that the frequency range may need to be adjusted based on the insertion depth in order to optimise performance. Compression of the frequency map may be advisable in cases where the insertion depth is limited, in order to include important speech frequencies. However, as there have only been a limited number of studies in this area, there is scope for further investigation of the optimal frequency range for individual CI users. Future studies should ideally include a measurement of the insertion angle of the device and allow time to adjust to the new sound. One limitation of the studies by Fu and Shannon and Başkent and Shannon mentioned above was that insertion angles were not measured and the insertion depths were assumed from the length of the devices. This is less than ideal, given the fact that insertion angles have been found to vary widely, even between individual recipients with the same device, as discussed in section 2.3.1. Therefore it is possible that the frequency maps which were called ‘matched’ maps were shifted relative to the Greenwood function, at least for some participants, and assumed insertion depths may not relate very closely to the actual insertion angles of the devices. The findings of these studies should be considered with this in mind.

2.9 Acclimatisation to the Implant Signal

The frequency allocation studies described above were mostly performed acutely, that is that participants were tested immediately after fitting each new map and no training or time was allowed to adjust to the new sound quality. A number of studies have looked at possible improvements in perception that may happen following a spectral shift as a result of training or use of the new map. This is known as acclimatisation.

A study published by Rosen *et al.* (1999) looked at the issue of adaptation to upward spectral shifts of speech in normal-hearing listeners. In their study, speech perception was investigated in young adults with normal hearing who listened to a four channel implant simulation with and without spectral shift. Participants received training with the CI simulation prior to speech perception tests in ten separate sessions. Significant improvements in performance were measured over the course of the study, although performance was still better for the unshifted condition, for both sentences and vowel recognition, at the end of the study. The authors noted that performance increased from near zero to about one-half the performance in the unshifted condition after just three hours of experience. This offers a possible explanation for the fact that CI users sometimes perform better with their processor map than the normal acoustic tonotopic map: CI users in all the studies referred to by Başkent and Shannon had considerable experience with their CI maps and therefore may have acclimatised to the CI frequency map.

Goupell *et al.* (2008) also looked at the effect of acclimatisation in a study with three normal-hearing listeners. They tested a matched condition as well as an expanded and a compressed condition. Significant improvements in sentence perception in noise were observed for the expanded and matched conditions, but there was no significant improvement in the compressed condition over the course of nine sessions (the first being the equivalent test session in an earlier experiment). For the matched condition, learning occurred over the first two sessions, and for the expanded condition learning occurred over the first three sessions. However, at the end of the course of nine sessions, performance with the matched map was still better than that with the expanded map.

Li *et al*. (2009) investigated the interaction between unsupervised learning and the degree of spectral mismatch in normal-hearing listeners. Subjects were tested on vowel recognition repeatedly over a five day period whilst being exposed to 8-channel, sine-wave vocoded speech. They found that subjects adapted completely to a shift of 3.6 mm but incompletely to a shift of 6 mm. For shifts beyond 6 mm, they found that some passive adaptation was observed when exposure to the severe shift was mixed with exposure to a smaller spectral shift, even when this was at the expense of some low frequency information. They concluded that the range of spectral mismatch that CI users can adapt to (without training) may be larger than previously reported.

A study by McKay and Henshall (2002) suggests that small frequency shifts can be accommodated by CI users within a limited time frame. In their study, frequency ratios up to 1.3 (equivalent to 0.4 octaves) were tolerated and accommodated by recipients within a two week period. However, one participant found a frequency shift with a ratio of 1.7 (equivalent to 0.7 octaves) too great to tolerate when wearing the map away from the laboratory.

A study by Reiss *et al*. (2007) shows that CI users can adjust their internal frequency map over a period of time. They performed frequency matching experiments in recipients of the Iowa/Nucleus Hybrid electrode which is only 10 mm long. Participants in the study were required to compare the pitch sensation produced by the electrical stimulation with the pitch of pure tones presented acoustically to the contralateral ear. Results were reported for eleven CI recipients who were able to perform the procedure. The results showed that after at least 12 months use of the device, pitch perceptions elicited by individual electrodes were closer to the frequency map assigned to the electrode than to the frequency which they perceived shortly after fitting, which was closer to the normal acoustic tonotopic frequency.

A further study by Fu and Shannon (2002) looked at the issue of acclimatisation in CI users with the Nucleus 22 implant. In their 2002 study, three Nucleus 22 users listened to a spectrally shifted map over a period of three months. Speech perception performance was measured before, during and after the three month period. It was found that performance improved over time and nearly reached performance with the normal clinical map on the consonant and HINT sentence tests. However, recognition of vowels and sentence perception for TIMIT sentences remained significantly below baseline performance. This suggests that acclimatisation to a spectrally shifted map may be slow and possibly incomplete for CI users.

Sagi *et al.* (2010b) applied a computational model of phoneme identification to the data collected in Fu and Shannon's 2002 study. In applying the model, they compared vowel confusion matrices collected over the 3 month study period with model matrices until the best fit had been obtained. The model had an internal noise component and a decision model component. They were able to show that there was more uncertainty in the responses with the shifted map than with the clinical map for all participants. One participant additionally showed incomplete adaptation to the basal shift for the experimental map. The model indicated that this was associated with reduced ability to identify the second formant (F2) of the vowel correctly. The paper goes on to discuss the merits of the individual maps and suggests that the experimental map would have given poorer performance than the clinical map because the positions of the first formant (F1) frequencies were altered relative to those of the second formant (F2). This indicates that performance with different frequency allocations in CI users can be affected by the relative positions of different frequencies, not just the effect of frequency shift and acclimatisation to it.

Harnsberger *et al.* (2001) assessed vowel spaces for CI users and found little evidence for lack of acclimatisation. CI users were asked to label synthetic vowels and then rate their 'goodness of fit' and from this, vowel spaces were constructed. With one exception, the authors found no systematic shifts in vowel space but instead they found that vowel spaces varied in the relative size of their vowel categories, suggesting individual differences in formant frequency discrimination.

Schvartz *et al.* (2008) found that the ability to recognise spectrally degraded phonemes was better for young normal-hearing listeners than for middle-aged and older normal-hearing listeners. Their simulation study was performed with thirty normal-hearing listeners. They found significant intra-group variability in the middle-aged and older groups; age was the primary factor contributing to performance but verbal memory abilities also contributed.

A functional magnetic resonance imaging study by (Eisner *et al.*, 2010) provides evidence that variation in successful processing of CI simulations can depend on high-level language processes that go beyond relatively early, acoustic-phonetic processes. In their study, normal-hearing listeners were trained with CI simulations of spectrally shifted speech and this was compared with adaptation to spectrally inverted speech. Considerable variability in the identification of words within sentences was observed during the course of the experiment. Some individuals showed considerable improvement in scores in the spectrally shifted condition (>60%), whilst others barely improved at all (<5%). The improvement was correlated with the amount of learning and with working memory capacity. Functional MRI performed concurrently found a correlation between activity in the left inferior frontal gyrus, which is implicated in higher-order language processes, and both learning score and working memory score.

In summary, there is evidence that CI users can adjust to a different frequency map over a period of time but the degree to which the individual is able to acclimatise may be limited if there is a large shift from the individual's internal frequency map, or if the CI frequency map is distorted or if the individual's capacity to adapt is limited.

2.9.1 Considerations for Unilaterally Implanted and Bilaterally Implanted CI Users

Whilst acclimatisation has been reported for unilateral CI users who are profoundly deaf in both ears, the situation may be different for bilateral CI users, or for unilateral CI users with significant residual hearing in their contralateral ear. Kan *et al.* (2015) reported that differences of insertion depth in bilateral CI users can cause problems with fusion of the auditory images from the two ears, which in turn can cause difficulties with the perception of binaural cues, which are necessary for localisation.

The studies reported above concern unilateral CI users. This study will also focus on unilateral CI users.

2.10 Evidence Contributing to Frequency Allocation Data from Other Studies

As there is an interaction between channel selection and frequency allocation, some additional information may be obtained from channel selection experiments. Gani *et al.* (2007) performed a channel selection experiment with five MED-EL Combi 40+ CI users. In the experiment, apical channels were progressively deactivated and speech perception was assessed. Pitch ranking was also measured. It was found that speech perception significantly improved in two participants when up to three apical electrodes were deactivated. Two possible explanations for this were given: firstly, that deactivation of the electrodes might have produced a reduction in frequency-to-place misalignment or, secondly, that in the normal map with all electrodes active, stimulation of the most apical electrodes might be activating the same population of neurons and therefore deactivation of one or more of them could improve pitch perception.

Lee *et al*. (2012) investigated the effect of using different areas of the cochlea for stimulation and found that the mid region of the cochlea offered better identification of words, vowels and consonants than either the apical or basal end. However, the mid region also represented the area with the smallest amount of frequency shift relative to the everyday map.

Finally, Jethanamest *et al*. (2010) developed a new software tool for optimisation of the frequency allocation for users of Nucleus cochlear implants. With Nucleus devices, a finite number of frequency tables are available and the frequency allocation is normally selected from one of these, although further adjustments are possible. Jethanamest *et al*. designed a software tool which enabled CI recipients to listen to speech using different frequency tables and to select the one which they preferred. In a pilot study with 11 Nucleus CI users, approximately half the users chose a table which was different from the default table but it is unclear if this resulted in any improvements in performance.

2.11 Summary and Rationale for Experiment 1: Fixed-Position Frequency Maps

The literature relating to pitch perception and CIs suggests that there are a number of different factors which affect pitch perception in CI users and these vary between individuals. Hence the ideal frequency allocation is also likely to vary between individuals. This is illustrated by the fact that pitch matching experiments have shown that the perceived frequencies from stimulation of CI electrodes is broadly in agreement with the Greenwood function for some individuals but not for others.

The current state of the literature is such that there are still unanswered questions relating to the adjustment of CI frequency allocations. Published studies of frequency allocation have generally not measured insertion angles or attempted to fit the frequency allocation to specific locations within the cochlea, even though a matching effect has been reported. Neither have CI users been given time to acclimatise to each new setting prior to measuring performance, in some of the studies described above. Additionally, there are reports of variations in pitch perception along the array for some CI users, which has not been taken into consideration.

In order to address these gaps in the literature, a study was designed to assess the performance of CI users with frequency maps adjusted to fixed positions in the cochlea, before and after a period of take-home experience. The study involved comparing a frequency map based on the Greenwood function with the implant's default frequency allocation. These frequency maps differ in three ways. Firstly, the default map allocates a larger proportion of the frequency range to the apical electrodes than the basal electrodes, whereas the proportion is relatively uniform for the Greenwood map. Whilst the default allocation ensures that fine structure cues are sent to apical electrodes, where they are most likely to be perceived (see Prentiss *et al.* 2014)), results reported in pitch-matching studies suggest that place-pitch perception tails off towards the apex and so the default allocation is not necessarily ideal (see section 2.5.3). Secondly, the default map uses all available electrodes and is not fixed to positions in the cochlea, whereas the Greenwood map is. Thirdly, as the Greenwood map covers a large area of the cochlea, the default allocation may be shifted towards the base relative to the Greenwood map.

It was anticipated that if the Greenwood function is a good match to an individual's frequency-to-place map, performance would be improved with a Greenwood-based frequency allocation. There would be an improvement in speech perception due to the map being 'matched' and there would be an improvement in frequency discrimination if the Greenwood map was expanded relative to the default map. Subjective sound quality might also be improved, as the map would be perceived as more natural. However, the literature does not suggest that this will be the case for all CI users. The Greenwood map may not represent a 'matched map' for some individuals or may result in sounds being allocated to areas of the cochlea with poor place-pitch perception. Additionally, fitting the Greenwood map could result in compromise to the map. For example, truncation of the frequency range will occur if the device is not sufficiently deeply inserted. Or a reduction in the number of active electrodes may result, as the Greenwood frequencies for basal electrodes may be beyond the frequency range of the device.

As the Greenwood map may not be ideal for all CI users, a further map was included in the experiment, which might be more suitable for those with shallow insertions, or with poor place-pitch perception at the apical end of the array, or whose frequency-place function falls considerably below the Greenwood function.

The data from previous pitch matching and frequency allocation studies suggest that logarithmic or near-logarithmic frequency spacing is appropriate for CI frequency maps. This is likely to be most true for widely spaced electrodes positioned along the lateral wall, such as in the MED-EL standard electrode array, where the effects of local variations in neural responses to the stimulation are limited by current spread. For those with poor place-pitch perception at the apical end of the array, the MED-EL default frequency allocation, with its bias towards the apical end of the array, may not be ideal. A frequency map with more uniform frequency spacing and which provides stimulation to a limited area of the cochlea may be more suitable. Such a map could ensure that stimulation is focussed on an area where SG cells are likely to be present and perception of changes in place-pitch are likely to be feasible along the length of the array. This map would not be matched to the Greenwood function, but instead would fall some way below it, which of itself could be more appropriate for some CI users. A map with these characteristics was derived by considering the area of the cochlea containing the SG. Further details are given in section 3.1.4.

The study was designed to assess performance with the different maps for perception of both speech and musical sounds. Alongside this, electrode discrimination was assessed, so that electrodes in areas of poor pitch perception could be identified, as poor pitch perception may limit performance.

2.11.1 Research Questions

The intention of the study was to collect data which would help to answer the following questions:

1. Should CI frequency maps be adjusted on an individual basis?
2. If yes, should the adjustment be based on the insertion angle of the device? Should the adjustment be to the Greenwood function or an alternative?
3. Do all participants perform better with the best frequency allocation for the group of participants or do some individuals perform better with a different frequency allocation?
4. Is it possible to predict which allocation will be best for an individual CI user?

2.11.2 Hypotheses

1. As CI users vary in frequency map, insertion angle, anatomy, cochlear health and acclimatisation, it is hypothesised that perception of speech and music will be improved, at least for some CI users, if frequency maps are adjusted on an individual basis.
2. Participants may have acclimatised to the default map to a greater or lesser extent. If an individual has acclimatised to the default map and does not have difficulties with pitch perception, the default map may offer the best performance of the three maps. If an individual has not acclimatised to the default map and their internal frequency map is still well-represented by the Greenwood function, it is hypothesised that adjustment of the frequency allocation to a Greenwood-based map will offer improved performance, so long as there is not too much truncation of the frequency range at the low frequency end.
3. For those with poor pitch perception towards the apex, an alternative map which allocates the frequency range to a more limited area of the cochlea, where SG cells are likely to be present, may be preferable. However, this map may be frequency shifted relative to a matched map. Time will be allowed for acclimatisation in view of this. In the literature cases were reported where matched frequency maps were significantly below the Greenwood function. For any participants in this position, this alternative map is likely to be closer to a matched map than the Greenwood map.
4. If the electrode discrimination test proves to be predictive of performance with different allocations, it may be possible to predict which frequency allocation will offer best performance to an individual.

Chapter 3: Experiment 1 Part 1: Fixed-Position Frequency Allocation Settings

3.1 Methods

3.1.1 Ethical Approval

Ethical approval for the study was obtained from the NHS National Research Ethics Service (reference 11/SC/0291), from the department's safety and ethics committee (reference number 1200) and from the University's Research Governance Office (reference number 8000). CI recipients whose X-rays were analysed consented for their pooled anonymized data to be published. Those who participated in the experiment gave written informed consent.

3.1.2 Participants

Twelve MED-EL CI users with standard electrode arrays were recruited for the experiment. The MED-EL standard electrode array has twelve electrodes, each spaced 2.4 mm apart with an active length of 26.4 mm and is designed to sit along the lateral wall. This device was chosen due to the flexibility of the frequency allocation setting and the long length of the electrode array. All participants were post-lingually deafened adults, had at least twelve months experience with their device and scored at least 80% correct on the BKB sentence test (Bench *et al.*, 1979) in quiet, at the start of the study. All had cochleostomy insertions with the exception of P2, who had a round window insertion. Participants' details are shown in table 4.

Table 4 Participants' details

Participant	Age at Start of Study	Gender	Aetiology	Duration of implant use (years)	Strategy	Unilateral or Bilateral
P1	64	Male	Menieres	12	FSP	Bilateral
P2	65	Male	Unknown progressive	1	FSP	Unilateral
P3	59	Female	Hereditary	2	FSP	Unilateral
P4	61	Male	Hereditary	1	FSP	Unilateral
P5	41	Female	Hereditary	3	FS4	Unilateral
P6	56	Female	Hereditary	1	FS4	Unilateral
P7	61	Male	Unknown progressive	2	FSP	Unilateral
P8	41	Female	Hereditary	3	FSP	Unilateral
P9	68	Female	Infection	3	FSP	Unilateral
P10	65	Female	Hereditary	3	FS4-p	Unilateral
P11	51	Female	Bilateral skull fracture	2	FSP	Unilateral
P12	83	Female	Otosclerosis	1	FSP	Unilateral

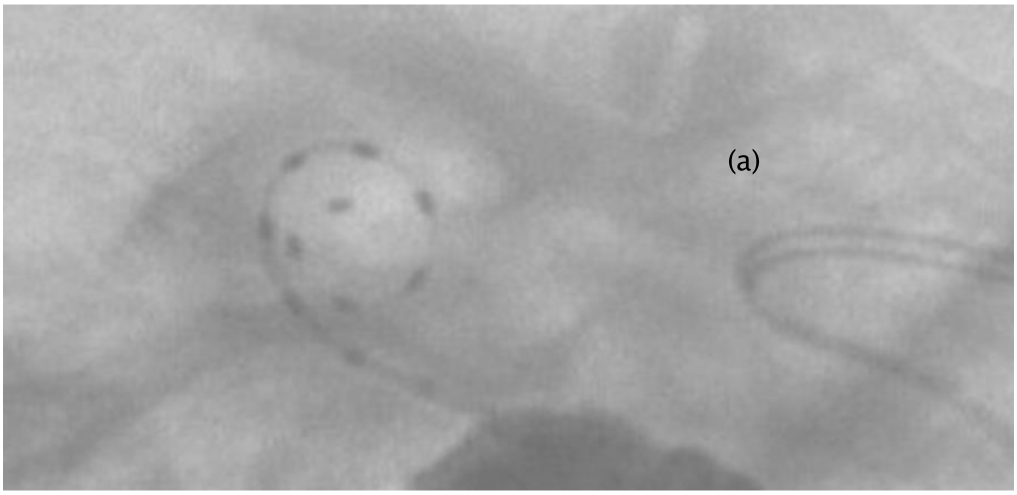
3.1.3 Radiological assessment

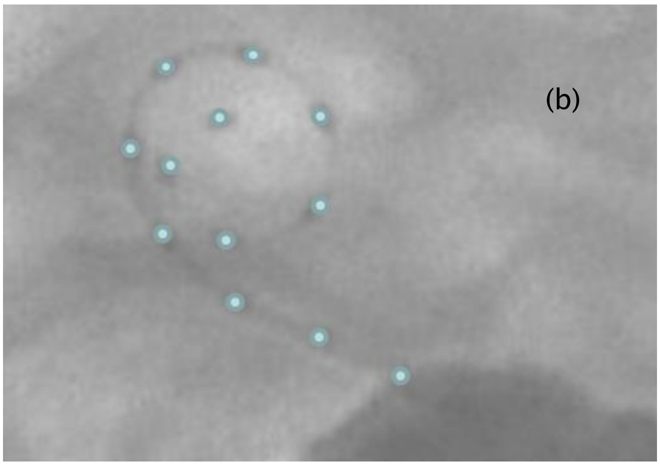
Post-operative X-rays are routinely collected as part of the clinical service and involve minimal radiation exposure. Prior to the main experiment, an experienced consultant radiologist reviewed X-rays for CI recipients with MED-EL standard electrode arrays, which had been implanted locally, and confirmed that these were of sufficient quality for individual electrodes to be identified in the majority of cases. A method of estimation of electrode insertion angle was developed and validated, which would not require the SSCC and vestibule to be identified for each individual X-ray. This was felt to be necessary as it is not possible to visualise the SSCC and vestibule on all post-operative X-rays.

Five X-rays were selected for analysis with good resolution and appropriate projection angles as visualisation of the electrode arrays with these X-rays was very good. One was a round window insertion; four implants had been inserted via a separate cochleostomy. In these cases the radiologist identified the likely position of the round window from the morphology; in some cases it was possible to visualise the SSCC and the vestibule, and it was found that a line joining these two points cut the electrode array at the anticipated position of the round window, as in Boëx *et al*. (2006).

The images were imported into Microsoft PowerPoint and the centre of each turn was determined from the centre of an oval positioned over the electrode positions, using the standard Windows drawing tools. The average angle between the most basal electrode and the round window, and the relative positions of the electrodes were found. The angles were measured relative to the position of the line joining the centre of each oval and the round window, as in Boëx *et al*. (2006). The anticipated position of the round window was further verified by superimposing the electrode positions onto a template of the cochlea from Kawano *et al*. (1996). It was found that the anticipated position of the round window from the X-rays was in very good agreement with the position of the end of the OC shown in the Kawano *et al*. template.

The position of the end of the OC can be taken as 0˚ for the purposes of calculation of Greenwood frequencies, but corresponds to approximately 10˚ relative to the 0˚ line given by the Cochlear View method, as described in Verbist *et al*. (2010). So, whilst the angles identified by the radiologist appear to be in agreement with the position of the end of the OC, they are not necessarily in complete agreement with the position of the round window. As the position of the end of the OC is what is required for calculation of the Greenwood function, the radiologist's view of the 'round window' was taken as the 0˚ line. Figure 12 shows the X-ray for participant P12, who participated in the main experiment, and also the positions of the electrodes and finally the same positions superimposed onto the shape of the template from Kawano *et al*., (1996). In this case, the surgeon reported that all 12 electrodes were intra-cochlear, whilst the radiologist felt that the most basal electrode was just beyond the round window.





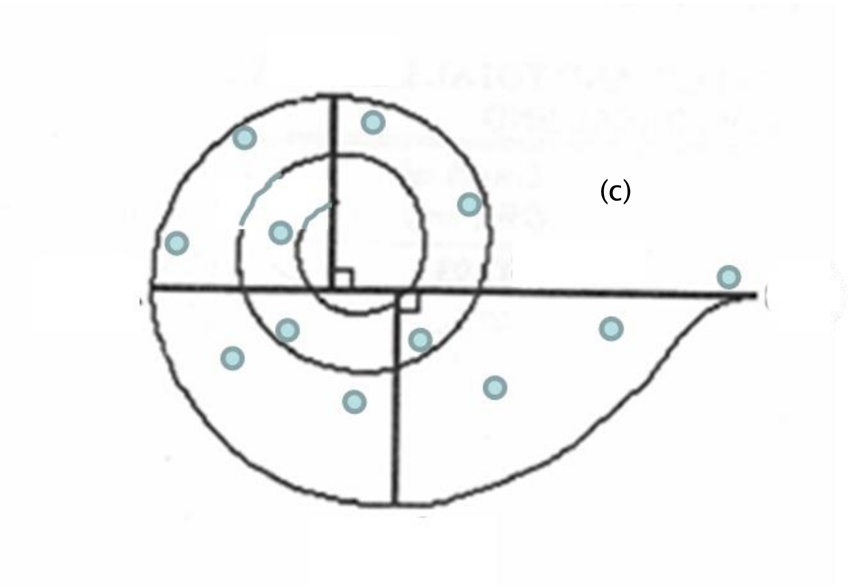


Figure 12 (a) X-ray for P12; (b) X-ray with electrode positions indicated (c) electrode positions superimposed on the shape of the template from Kawano *et al.* (1996)

The mean data for electrode angles for the five electrode arrays analysed is shown in Figure 13.

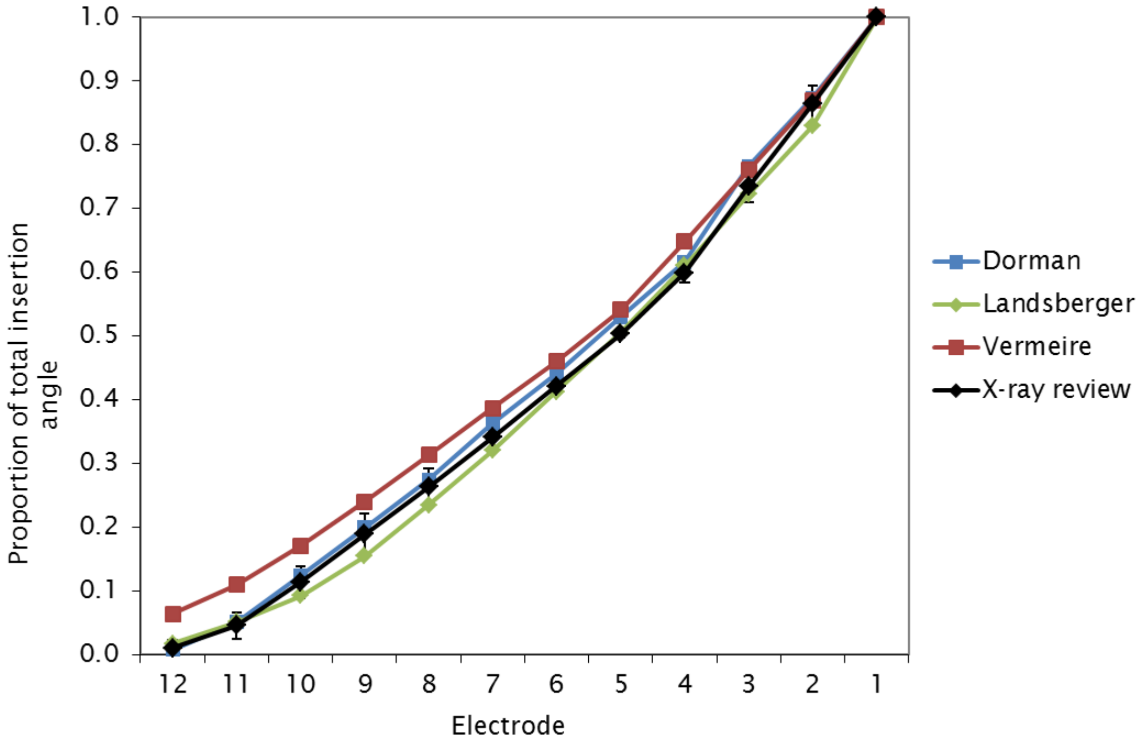


Figure 13 Mean insertion angles as a proportion of the total insertion angle (measured from the base) for electrodes for five X-rays included in the review and those for the recipient in Dorman *et al.* (2007), Landsberger *et al.* (2015) and Vermeire *et al.* (2008). Error bars = 1 standard deviation.

It can be seen that the average angles between electrodes for the five electrode arrays analysed by the radiologist were relatively constant in both turns but were larger in the middle turn. The point at which the electrode array entered the middle turn varied between studies. The results for this study were similar to the angles for the participant in Dorman *et al.* (2007) and were between those reported from the studies by Landsberger *et al* and Vermeire *et al.* The most basal electrode was typically close to the round window and had a very small insertion angle (approximately 1% of the total insertion angle).

For the X-rays for participants in the main experiment, experiment 1, only the angle between the most basal and most apical electrode was measured. The angles of the intermediate electrodes were assumed to be at the same proportions of the total insertion angle as for the reviewed X-rays. For fully inserted arrays, the angle between the round window and the most basal electrode was assumed to be at 1.1% of the total insertion angle, which was the mean value for this angle in the earlier review. For three electrode arrays which were reported as partially inserted by the surgeon, information about the insertion from the surgeon's intra-operative report was used to estimate the angle between the most basal electrode and the round window. Details can be found in Table 5.

Table 5 Radiological details for participants in experiment one

Participant	Image type	Intra-cochlear electrodes reported by surgeon	Intra-cochlear electrodes reported by radiologist	Angle between apical and basal electrodes	Distance between round window and basal electrode	Estimated insertion angle	Measured insertion angle based on radiologist's information
P1 left	Film	12	12	602˚	Not known	609˚	Not available
P1 right	Film	8-9	9	305˚	0 mm	308˚	339˚
P2	Digital	12	12	635˚	~ 1 mm	642˚	640˚
P3	Digital	12	12	564˚	1 – 2 mm	570˚	569˚
P4	Digital	12	12	698˚; scaled up from electrodes in the basal turn	~ 1 mm	706˚	Not available; likely to be less than 706˚
P5	Digital	11	10	441˚	1 – 2 mm from E10	441˚	437˚
P6	Digital	11	11	482˚	Between E11 and 12	482˚	485˚
P7	Digital	12	12	602˚	~ 3 mm	609˚	627˚
P8	Film	12	12	697˚	< 1 mm	705˚	699˚
P9	Film	12	12	675˚	< 1 mm	683˚	677˚
P10	Digital	12	11	432˚	Between E11 and E12	437˚	428˚
P11	Digital	12	12	565˚	<1 mm	571˚	567˚
P12	Digital	12	11	562˚	E12 just outside round window	568˚	560˚

Of the 12 CI recipients who were recruited, ten had X-rays which were of sufficient quality to allow the most apical and basal electrodes and the position of the round window to be identified by the consultant radiologist, who had performed the X-ray review. In these cases, the difference between the estimated angle between the round window and the most basal electrode, and the angle determined by the consultant radiologist, was small (mean absolute error = 6.1˚, range 1-18˚). The estimated insertion angle was used to calculate the frequency maps used in the experiment and was also included in the data analysis. In the case of the two participants with poor quality X-rays (P1 bilateral and P4 unilateral), both the clinical scientist and the radiologist had difficulty visualising some electrodes for these participants. Their data were excluded from the data analysis.

3.1.4 Frequency allocations

Three different maps with different frequency allocations were tested during the experiment. One of these was the participant's everyday clinical map, usually the default map, which was presented as a new map and trialled for at least six weeks so as to reduce bias based on the idea that a new map would be better.

The first of the alternative maps was a mapping to the Greenwood function, using the function expressed as a proportion of cochlear length (a=2.1; A=165.4; k=0.88) and data from table two of Kawano *et al.* (1996) to convert between angles and a proportion of cochlear length. Kawano *et al.*'s data were used as the position of the electrodes relative to the round window, for the X-rays in the review, showed very good agreement with the cochlear template, shown in figure 4A of Kawano *et al.* (1996). However, it should be noted that whilst Kawano *et al.* found the proportion of basilar length for each quarter turn of the spiral, the centre of the spiral was only corrected for each full turn for the X-rays used to calculate the proportions of the total insertion angle for individual electrodes. Hence the positions along the basilar membrane for study participants are not precise.

The second alternative map was calculated using equation 2 above from Sridhar *et al.* (2006). This equation was applied to the proportion of cochlear length (along the OC), prior to the calculation of the Greenwood function for the 'spiral ganglion' ('SG') map, such that the Greenwood function was calculated as a proportion of SG length. The result was a compressed map, allowing the processor's frequency range to be presented to the area of the cochlea over which SG cells are likely to be present. This also represents the area over which CI recipients are most likely to be able to perceive differences in place-pitch (Kalkman *et al.*, 2014). The insertion angle required to map all of the processor's frequency range was 746˚ for the Greenwood map and 526˚ for the SG map. For both the Greenwood and SG maps, the function relating electrode number to lower frequency boundary was approximately exponential (R^2 = 0.9991 for the Greenwood map and R^2 = 0.9997 for the SG map, for an insertion angle of 526˚). Lower frequency boundaries for these maps are shown in Figure 14.

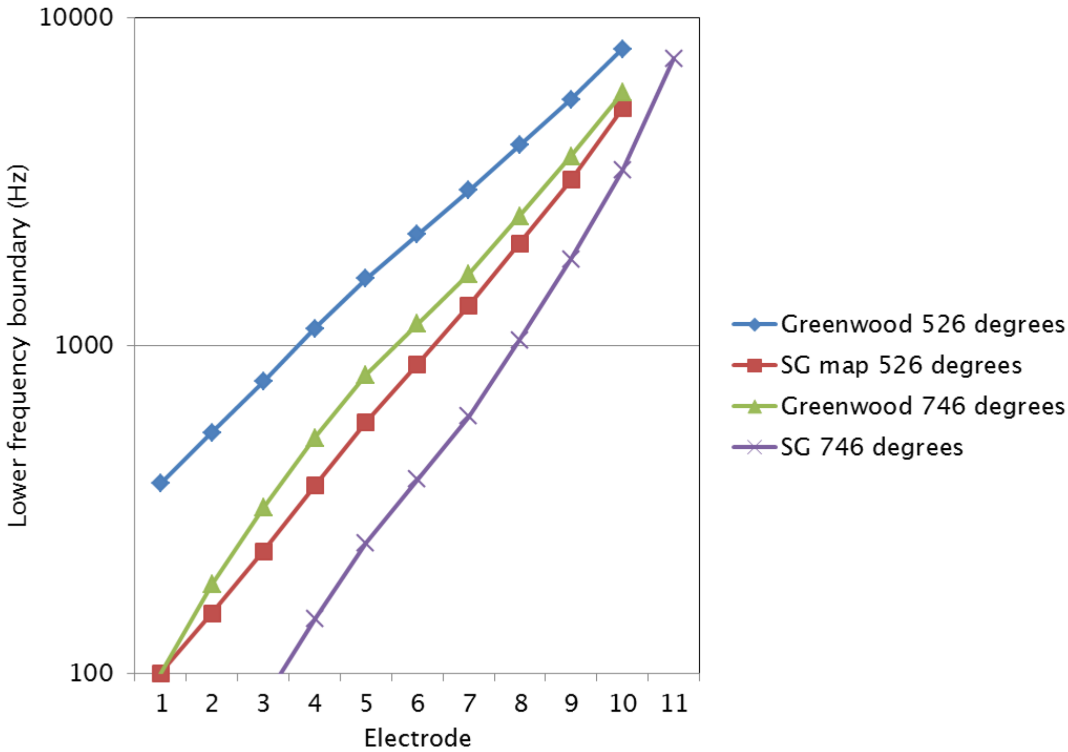


Figure 14 Lower frequency boundaries for the Greenwood and SG maps for two different insertion angles

The frequency range offered for the three alternative maps did not exceed the default frequency range (100 to 8500 Hz). The clinical map had the default shape in all cases: it used the Opus 2 default range of 100 to 8500 Hz in nine cases and the largest available range of 70 to 8500 Hz in one case (P8). The centre frequencies (Hz) of individual channels for the study maps for participants P10 (shallowest insertion) and P8 (deepest insertion) are shown in Table 6. Map details for all participants are given in Appendix 3.

Table 6 Channel centre frequencies (Hz) for participants P8 and P10

Electrode	1	2	3	4	5	6	7	8	9	10	11	12
P10 Clinical	154	278	448	673	986	1406	1978	2714	3858	5238	7335	off
P8 Clinical	125	234	385	582	840	1182	1631	2227	3064	4085	5656	7352
P10 Greenwood	720	992	1356	1927	2535	3342	4325	5656	7352	off	off	off
P8 Greenwood	182	304	489	760	1107	1559	2264	3452	5164	7346	off	off
P10 SG	216	317	479	736	1103	1586	2345	3468	5482	7352	off	off
P8 SG	Off	off	136	230	370	569	932	1606	2805	5932	7352	off

The frequency range varied for the Greenwood and SG maps between participants as these maps were in fixed locations and the frequency range therefore depended on the insertion angle of the most apical electrode. Participants with deeper insertions had access to a larger frequency range than those with shallow insertions for the Greenwood map (see table 5). Participants had one or two basal electrodes deactivated for the Greenwood and SG maps as the frequencies calculated for the most basal electrodes were beyond the permitted frequency range; similarly participants had one or two apical electrodes deactivated for the SG map but never more than three electrodes deactivated in total. The mean number of electrodes was 11.5 for the clinical map (range 10 to12); 9.5 for the SG map (range 9 to10) and 9.7 for the Greenwood map (range 9 to10). Deactivation of electrodes meant that stimulation was restricted to a smaller area of the cochlea for the alternative maps than for the clinical map and in particular that there was no stimulation close to the round window. In cases where the frequency range presented was unchanged (e.g. for the SG map in most cases) but the area of the cochlea being stimulated was reduced, this resulted in frequency compression. In addition, a reduction in the number of electrodes produced increases in the rate of stimulation for the remaining active electrodes, especially with the FSP strategy. Additionally the number of 'fine structure channels' (apical electrode channels in which pulse rate is not fixed but is tied to changes in frequency, as described in section 2.4.2), was affected by adjustment of the frequency allocation. The number of fine structure channels was increased in six cases with the SG map and in one case with the Greenwood map; it was reduced in seven cases with the Greenwood map; for the participants with the FS4 and FS4-p strategies (in which the number of fine structure channels is usually four), the Greenwood map resulted in a reduction in the number of fine structure channels. This could have resulted in an increase in access to temporal pitch cues for some participants with the SG map but a reduction for in some cases with the Greenwood map. This is likely to be a relatively weak pitch cue (see Riss et al. (2011), for example). Details of the map parameters for the three maps are given in table 7.

Table 7 Details for parameters for the three maps investigated in experiment 1 part 1

Parameter	Clinical map	SG map	Greenwood map
Lower boundary of the frequency range	100 Hz (except for P8 = 70 Hz)	Ranges between 100 and 175 Hz	Ranges between 133 and 608 Hz
Upper boundary of the frequency range	8500 Hz	8500 Hz	8500 Hz
Number of electrodes	10 to 12 (mean = 11.5)	9 or 10 (mean = 9.5)	9 or 10 (mean = 9.7)
Number of fine structure channels	1 to 4 (mean = 2.6)	2 to 4 (mean = 3.4)	0 to 2 (mean = 1.3
Rate of stimulation for those using the FSP strategy	1130 Hz to 2814 Hz (mean = 1738 Hz)	1130 to 2715 Hz (mean = 2113 Hz)	1130 to 2715 Hz (mean = 1857 Hz)

An additional consideration in relation to the effect of fitting the frequency allocations is the extent to which requested frequency boundaries were realised by the CI filters present in the individual's processor. The filters used by MED-EL devices are FIR (Finite Impulse Response) digital filters which are not always able to exactly match the requested frequency. The extent to which the requested lower frequency boundary was realised for the Greenwood and SG maps was investigated and is shown in Figure 15, for those with electrodes one to ten active in the Greenwood map. Electrodes 11 and 12 were deactivated in all cases with this map and E10 was deactivated in three cases. The mean error across all ten participants averaged over all active electrodes was less than 2% for the SG map and less than 3% for the Greenwood map (range 0 to 5% across all maps). The error was much larger on the most basal electrode for the SG and Greenwood maps due to the upper boundary of the frequency range being fixed at 8500 Hz. For the majority of electrodes, the mean error in the realised lower frequency boundary was less than 1% with these maps.

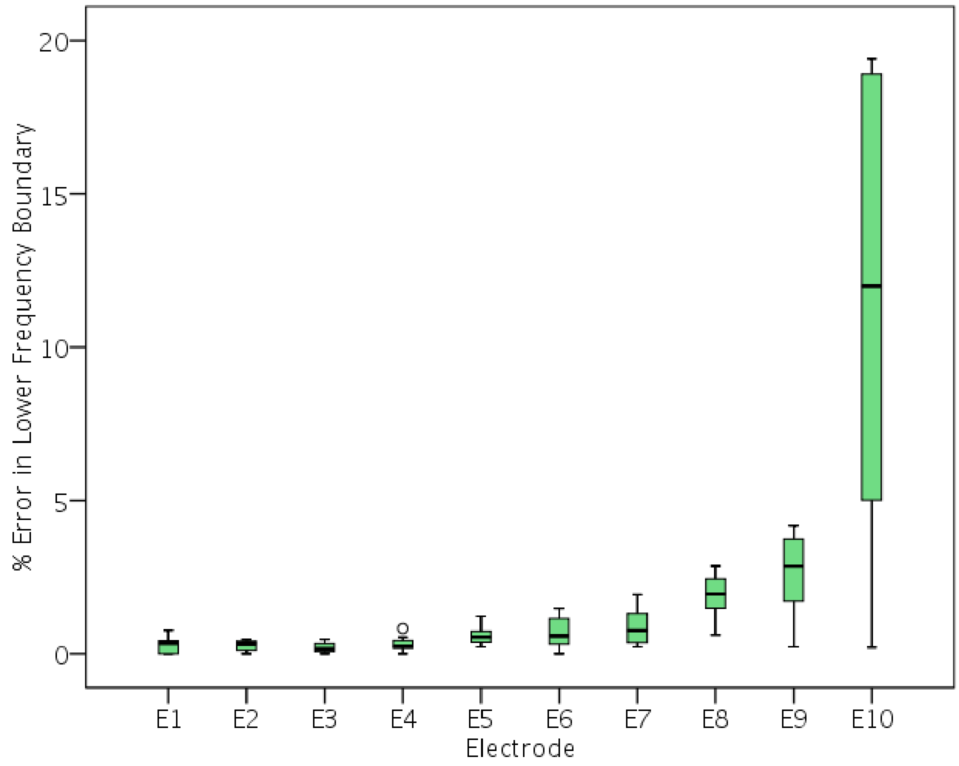


Figure 15 % Difference Between the Requested and Realised Lower Frequency Boundary for the Greenwood map

An example is shown in Figure 16. This figure shows the frequency map for the Greenwood map for P2, as displayed in the tuning software. The centre frequency for each filter is shown by a line intersecting the bar representing the frequency range assigned to each electrode. A logarithmic scale is used for the frequency axis. The consequence of the error in the realised frequency for Electrode (E) 10 was that part of the frequency bandwidth for E10 was allocated to both E9 and E10.

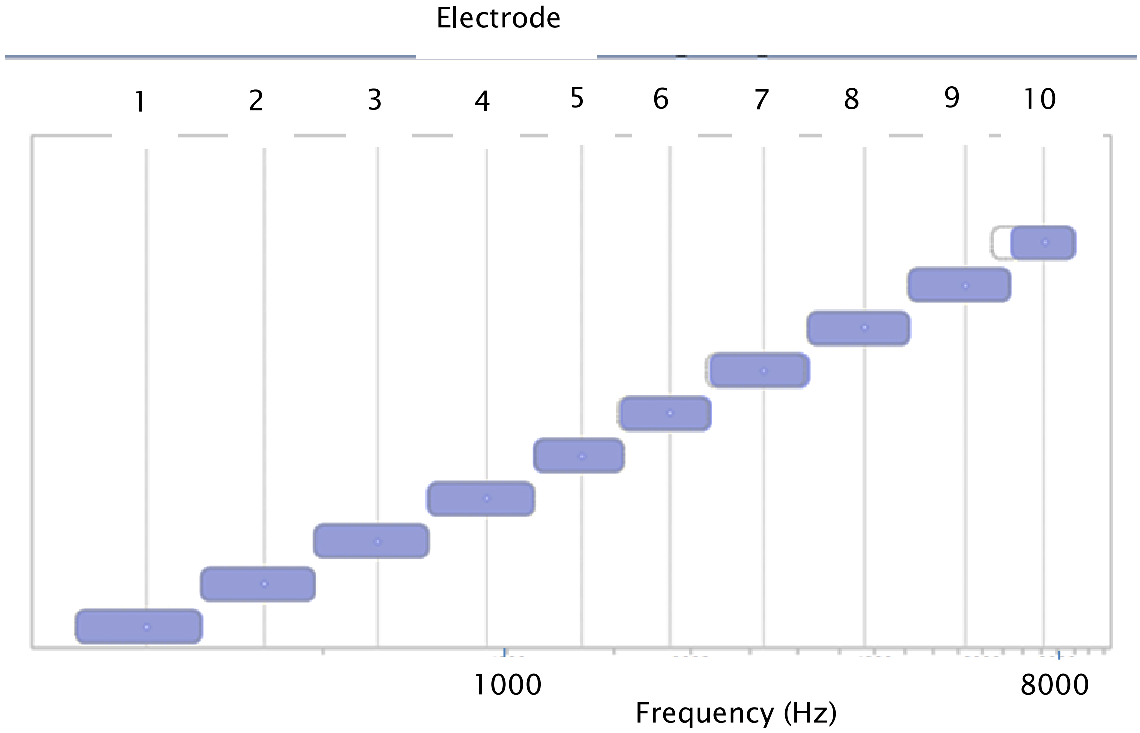


Figure 16 Greenwood map for P2 showing frequency boundaries for individual electrodes

3.1.5 Map Trial Periods

Participants attended the centre on four occasions and a study map was downloaded to their processor during each of the first three sessions, to enable them to try the map for the trial period. The order in which participants tried these maps was balanced and assigned pseudo-randomly. Trials of the study maps lasted for at least six weeks (mean time of use = 7.9 weeks, range 6 to13 weeks), during which participants were encouraged to use the study map but could return to their clinical map if they wished to. Instructions for participants were 'Please use the new map as much as you feel able to over the next few weeks and compare it with your everyday map in programme… It may take some time to get used to the new map (at least a few days), so please do give it a good try. If you find the sound quality unacceptable, however, do feel free to return to your everyday map.'

3.1.6 Assessments

Four outcome measures were used with each map: two speech perception tasks, which have previously been found to be sensitive to changes of frequency allocation (see for example, Başkent and Shannon (2004)), a discrimination task for different piano notes and a subjective rating of sound quality. A pitch matching task was not included as all participants were profoundly deaf in both ears and therefore would have been unable to perform a procedure which involved comparing electric stimuli with acoustic stimuli. The speech perception measures were the BKB sentence test (Bench *et al.*, 1979) in speech-shaped noise and an eight alternative forced choice test of vowel perception. The BKB sentence test and the piano test were performed initially after fitting and at the end of each trial, whereas the vowel test was performed at the end of each trial only (due to technical difficulties). The map quality questionnaire was completed at the end of each map trial. Additionally, electrode discrimination was assessed for each pair of neighbouring electrodes.

3.1.7 BKB Sentence Test

The BKB sentence test was spoken by a male speaker and presented in speech shaped noise, which was based on the male voice. The test was performed in a sound treated room, from a Tannoy V12 BLK loudspeaker at 0° azimuth, with each participant seated on the calibrated spot. Speech was presented at 65 dB(A); calibration was to the speech shaped noise at the calibrated spot. The signal-to-noise ratio (SNR) used for the experiment, for each individual, was determined adaptively using single lists of sixteen sentences with the clinical map, such that the SNR gave a score between 60 to 70% correct with the clinical map on a single list. Two lists of sixteen sentences each were presented to assess performance each time the test was administered giving a total maximum score of 100 key words correct, using loose scoring. Patients at the centre had previously performed the test on several occasions, with different lists each time, so a learning effect on the test was unlikely. List numbers were incremented to avoid repetition.

The signal spectrum for the noise file, which is based on the talker in the test, is shown in Figure 17. It is possible to see that the speech frequencies with the highest amplitudes are between 0 and 1 kHz. The average first formant (F1) has a frequency of 534 Hz, the average F2 has a frequency of 1372 Hz and the average F3 has a frequency of 2413 Hz.

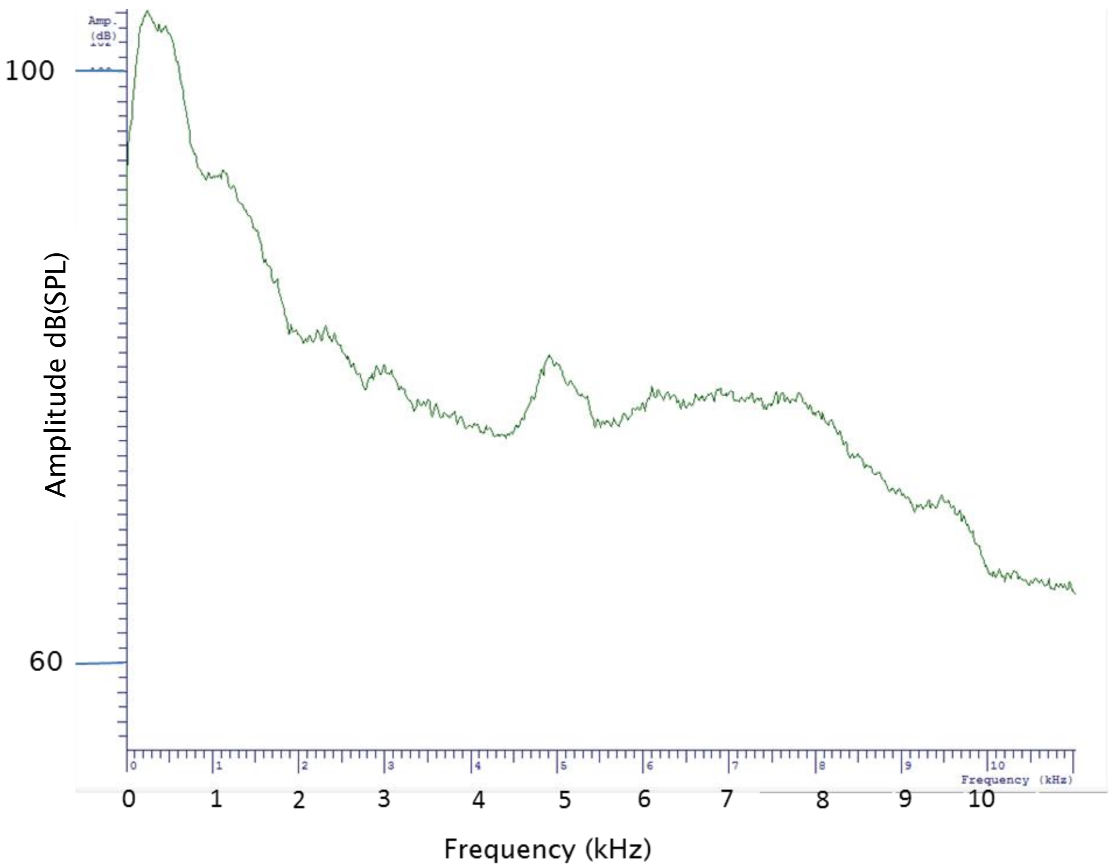


Figure 17 Signal spectrum for the speech-shaped noise used with the BKB sentence test

3.1.8 Vowel Test

The vowel identification test was an eight alternative forced choice test, spoken by a female speaker, and presented using the same soundfield arrangement as for the BKB sentence test, with mean vowel presentation level of 65 dB(A). Each vowel was preceded by /h/ and followed by /d/, giving the following tokens: 'heed', 'head', 'hid', 'heard', 'hood', 'who'd', 'had' and 'hard'. Each token was presented five times in random order during each test. Participants selected their choice of token from a graphical user interface on a touch screen monitor. The graphical user interface (GUI) for the test is shown in Figure 18.

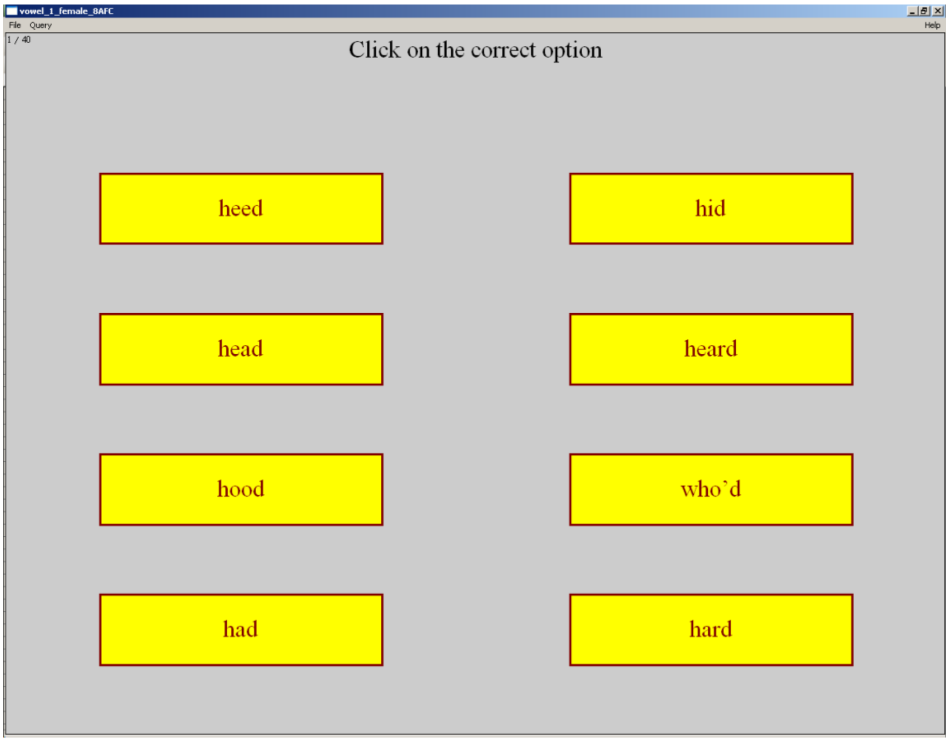


Figure 18 GUI for the vowel test

Spectral analysis was performed for all the vowel tokens used in the test. Spectral analysis for the vowel /a/ from 'hard' is shown in Figure 19. The formants can be seen as peaks in the amplitude spectrum and the formant frequencies are shown in Table 8.

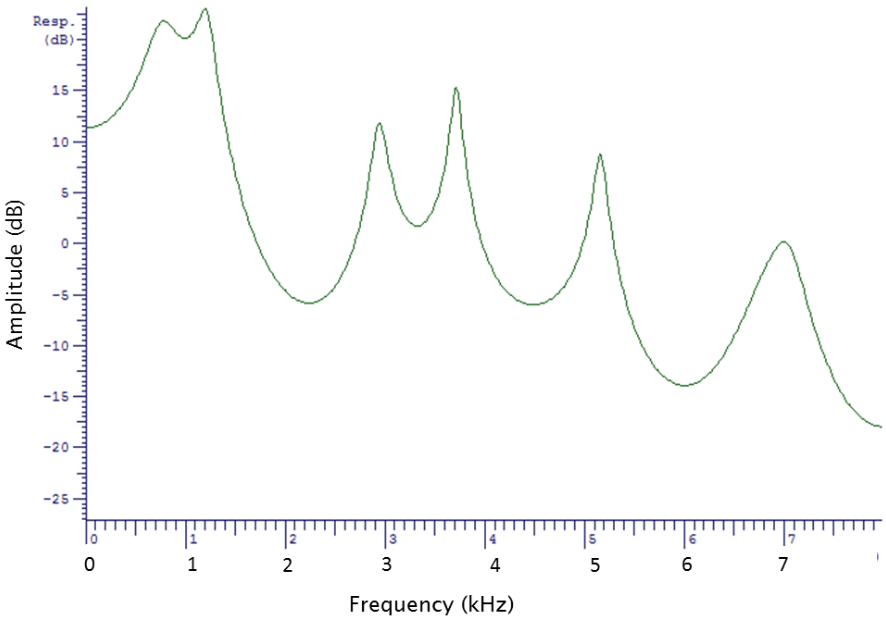


Figure 19 Frequency analysis of /a/ from 'hard'. Amplitude peaks are the formants (given in dB(SPL)). Fundamental frequency F0 = 160 Hz.

Table 8 Vowel formant frequencies for the tokens used in the vowel test

Word	F1 (Hz)	F2 (Hz)	F3 (Hz)
Had	1009	1765	2981
Hard	777	1217	2943
Head	603	2196	2986
Heard	593	1541	2886
Heed	361	2588	3375
Hid	427	2555	3059
Hood	462	1270	2718
Who'd	336	1449	2681

As the first formant frequencies were between 336 and 1009 Hz, some first formants would have been inaudible for participants with shallow insertions for the Greenwood map (the highest lower frequency boundary was 608 Hz).

3.1.9 Discrimination Test Using Piano Notes

The piano notes discrimination test that was a modified version of the pitch test from the South of England CI Centre Music Test Battery (SOECIC MTB)(van Besouw and Grasmeder, 2011). The pitch test in the SOECIC MTB is an adaptive 3I3AFC (3-interval, 3-alternative forced choice) test. The participant is asked to identify the odd note out when 3 notes are presented consecutively, separated by a short gap. The test uses an adaptive 2-down, 1-up algorithm which converges on the 71% correct level. The stimuli were generated using the HALion One synthesizer in Cubase and varied from 1600 cents to one cent from the reference frequency. For the purpose of this experiment, only one reference note was used, as compared with three in the original test. Also, all comparison stimuli were higher in pitch than the reference, which was not the case in the original test. The reference frequency used was 350 Hz. This frequency was chosen as it is above the range over which CI users typically have access to pitch cues from temporal variations in the amplitude envelope (Shannon, 1983). The sound file containing each note was 1.3 s in length and the gap between the sound files was 0.5 s. The odd note out was randomised to the first, second or third test interval for each trial. Twelve reversals were recorded and the last ten were averaged to find the participant's score. Larger step sizes were used in the first two reversals. Random variation of loudness of ± 3 dB was incorporated into the test to mask any possible loudness cues. The reference stimuli was presented at a level of 60 dB(A) and comparison stimuli were calibrated to within ± 3 dB of this level as described in Appendix 5. Participants were given sufficient practise trials to feel confident of the task before the first test in session 1.

The GUI for the participant is shown in Figure 20.

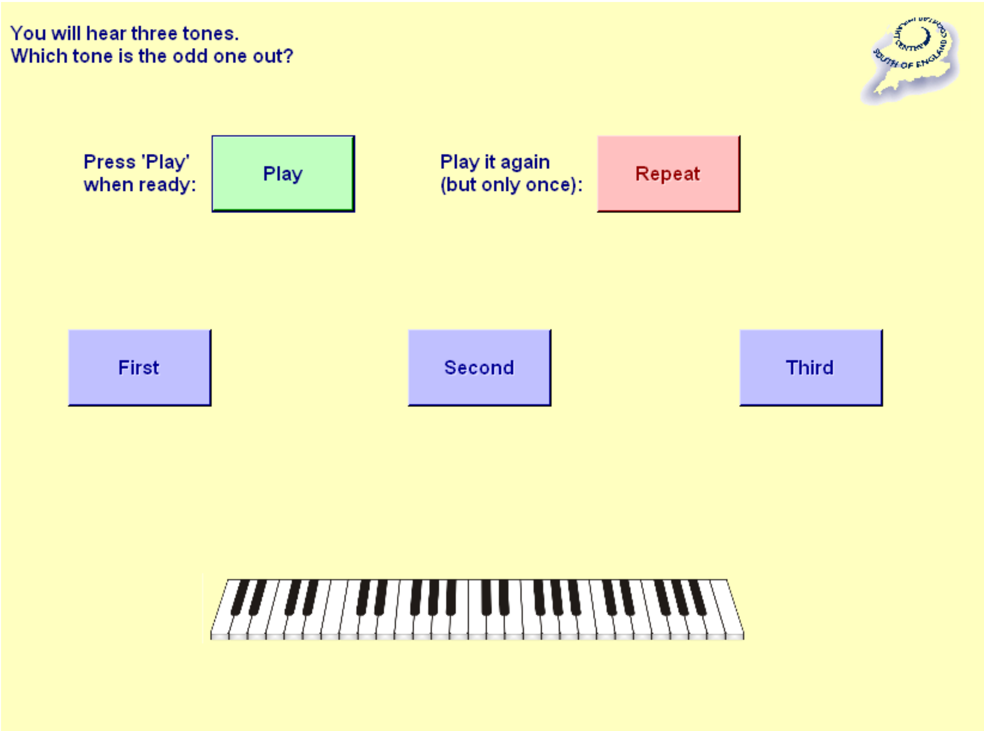


Figure 20 GUI for the piano test

The test is not a pure pitch discrimination task owing to differences in timbre of stimuli of different frequencies. The waveform of the sound one semitone (100 cents) above the reference is shown with the reference waveform in Figure 21.

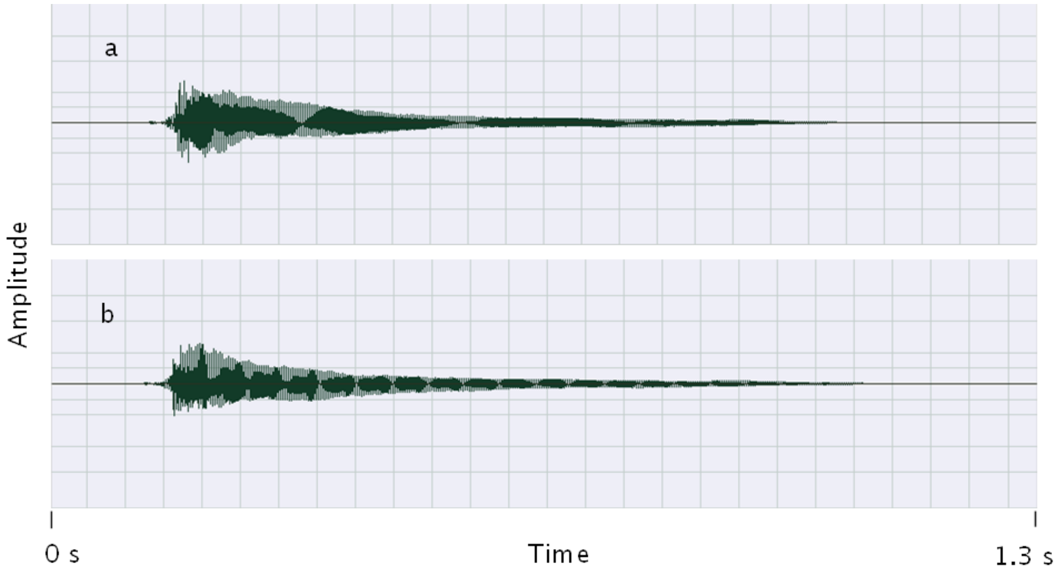


Figure 21 Waveform of (a) the stimulus 100 cents above the reference and (b) the reference stimulus for the piano notes discrimination test

3.1.10 Map Quality Questionnaire

The map quality questionnaire contained only two questions. ‘How often have you used the new map?’ had five possible answers of ‘very little’, ‘less than half the time’, ‘about half the time’, ‘more than half the time’ and ‘all the time’, and the participant ticked a box to give their answer. The second question, ‘How do you rate the sound quality of the new map?’ was recorded on a visual analogue scale, which extended from ‘very poor’ on the left side of the page to ‘very good’ on the right side of the page. The map quality questionnaire is shown in appendix 4.

3.1.11 Electrode Discrimination Test

The electrode discrimination test was administered as a variation of the pitch test from the South of England CI Centre Music Test Battery (van Besouw and Grasmeder, 2011). The pitch test is a 3I3AFC test. The participant was asked to identify the odd note out when three notes, each of one second duration, are presented consecutively, separated by a short gap, in random order. The original test runs adaptively, using a ‘two-down, one-up’ procedure, which converges on 71% correct, but for this task it was re-configured for the method of constant stimuli. Eight trials were run for each pair of electrodes, and the electrode pairs were tested in a pseudo-randomised order. Stimuli were pure tones of 1125 and 1500 Hz: in each case only the two electrodes being tested were activated in the participant's map and the frequency boundaries were adjusted so that these frequencies represented the centre of each filter. The strategy was adjusted to high definition Continuous Interleaved Sampling (HD-CIS) and each pair of electrodes was loudness balanced at 90% of the dynamic range prior to the test; during the test the full dynamic range was used. Tones were presented via circumaural headphones, Sennheiser HD570, worn over the processor. The choice of headphones for presentation of the stimuli was made after considering the alternatives. Soundfield presentation may have resulted in standing waves in the soundfield, as the stimuli were pure tones. Headphone presentation avoided the need for direct stimulation of the implant, which cannot be performed using the standard tuning software. The other alternative would have been the use of a direct input into the speech processor. However, this option would not necessarily be straightforward to calibrate. So, headphones were used. The reference tone was calibrated to 60 dB(A) and the comparison tone was calibrated to the equivalent level within the processor ± 1 dB, taking account of the microphone frequency response and the processor's frequency shaping filter. Additionally, intensity level was roved by ± 3 dB.

Details of the calibration of the pure tones used in this test are as follows.

In order to calibrate the tones, an Opus 2 processor was placed on the pinna of a manikin (KEMAR) and the output from the front end of the processor was taken via a custom made lead to the line-in on a computer, as shown in Figure 22. An initial adjustment was made following measurements on a single processor. The output of 3 processors of the same type was then measured for each sound stimulus. The Average RMS power in dB was recorded in Adobe Audition during the steady state part of the sound. Following this further adjustments to the sound levels and measurements were made as necessary. Details of the difference in sound level between the reference and target tones are shown in Table 9.

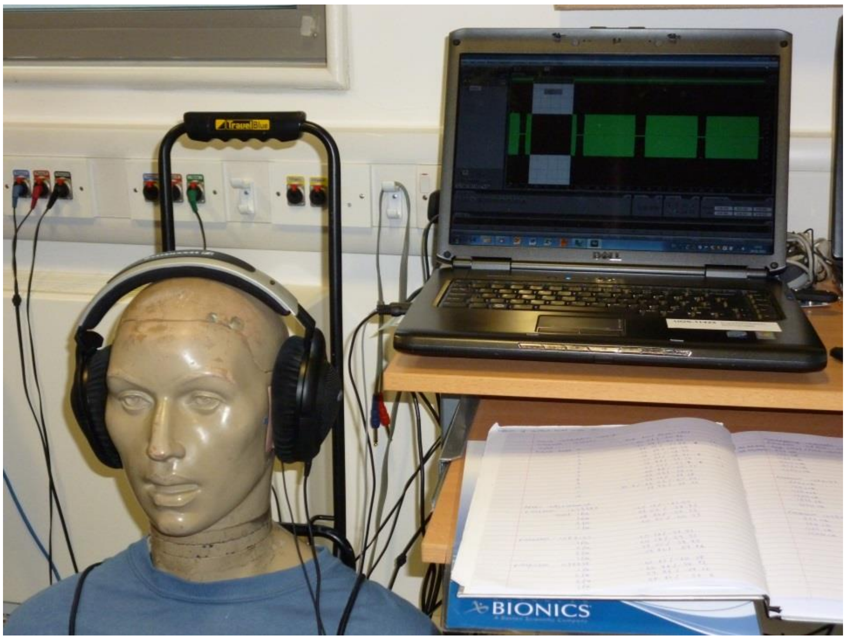


Figure 22 Calibration Setup for the Electrode Discrimination Test

Table 9 Difference in RMS power between the Reference and Target stimuli following calibration, for the Electrode Discrimination Test

Reference stimulus RMS power – target stimulus RMS power (dB)		
Processor 1	Processor 2	Processor 3
0.1	-0.1	0.3

These measurements indicated that the comparison sound stimulus had been successfully calibrated to within ± 1dB of the reference stimulus. The inverse of the processor's frequency shaping filter was then applied to the two sound files.

3.2 Results

3.2.1 Statistical Analysis

Statistical analysis was performed using repeated measures ANOVA and ANCOVA where results were normally distributed and Mauchly's test of sphericity gave a non-significant result; the effect sizes, *r*, for post-hoc tests following ANCOVA were calculated from the *F*-values for within-subjects contrasts. Pearson's correlation coefficient was used for correlations between variables which were normally distributed and paired *t*-tests (2-tailed) were used to compare two variables which were normally distributed. Where the Shapiro-Wilk test showed that data were not normally distributed, Friedman's test and Wilcoxon's signed rank test were used. The effect size has been reported as '*r*' for this test. The non-parametric Mann-Whitney *U* test was used to compare results for independent samples.

As there were only ten participants for whom data was analysed, the study was under-powered. The power of a 2-tailed Pearson correlation test with ten participants is only 0.33 for a large effect (r=0.5) with α=0.05 and is even less (0.13) for a medium effect (r=0.3). A much larger sample would be needed to achieve a power of 0.8 (29 participants for a large effect and 84 for a medium effect). Also for ANOVA: a repeated measures design with 10 participants has power of 0.34 for a medium effect for within-subject factors (assuming the correlation between measures = 0.5) but the power is less for an interaction between individuals (for example, if three groups were compared, it would be 0.22, making the same assumptions as before). Due to the underpowered nature of the analysis, Bonferroni corrections were avoided. For post-hoc tests following ANCOVA, the less conservative Sidak corrections were used. For correlations, no corrections were used but if the use of Bonferroni corrections would have resulted in an effect not being classed as significant, this is indicated in the text.

Data is displayed as boxplots, bar graphs or scatterplots. For the boxplots, boxes indicate the interquartile range; the solid line within each box indicates the median value. Whiskers represent the range of data, unless this extends beyond 1.5*the inter-quartile range from the box, in which case data points are considered to be outliers and are displayed as small black-filled circles. The small white-filled circles are individual data points which are not considered to be outliers.

3.2.2 Reported Map Use

Reported map use from the map quality questionnaire is shown in Figure 23 for the clinical, SG and Greenwood maps. Friedman's test confirmed that there was a significant effect of frequency allocation on the reported amount of use [$\chi^2(2)=13.3$, $p<0.001$]. Wilcoxon signed rank tests showed that the Greenwood map was used significantly less than the clinical map [$Z=-2.724$, $p=0.006$, $r=-0.61$, a large effect], as was the SG map [$Z=-2.116$, $p=0.034$, $r=-0.47$, a medium effect]. The effect seen with the SG map would not have been regarded as significant if Bonferroni corrections were used.

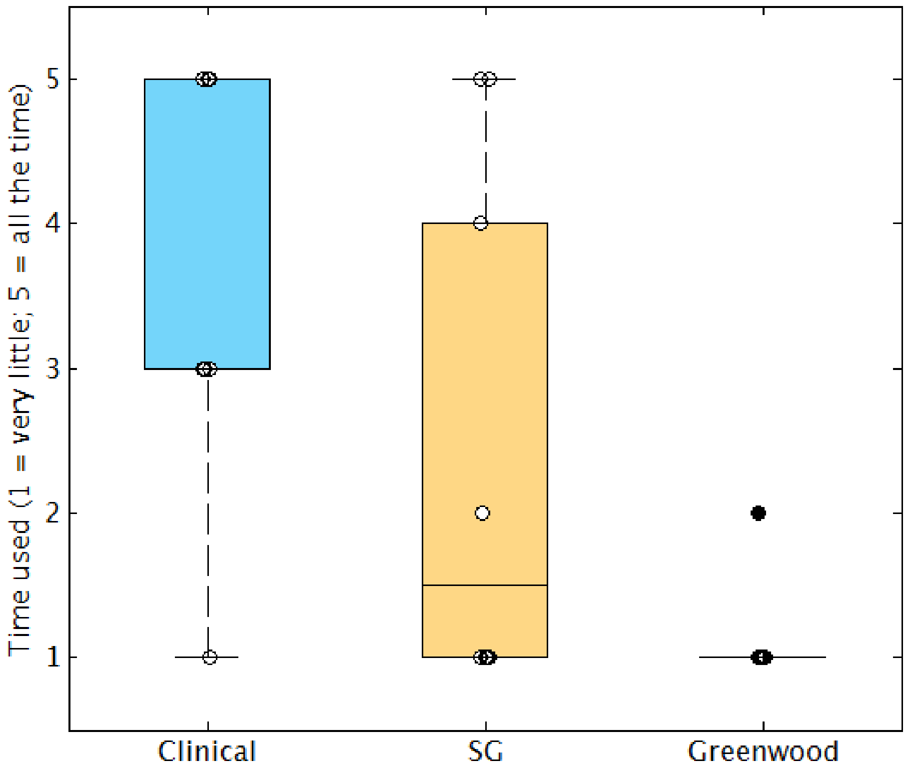


Figure 23 Map use with the clinical, SG and Greenwood maps as reported on the map quality questionnaire. For information relating to the interpretation of boxplots, see section 3.2.1.

3.2.3 Map Quality Rating

Participants' rating of the quality of each map is shown in Figure 24. A repeated measures ANOVA confirmed that there was a significant effect of frequency allocation on map sound quality rating [$F(2,18)=14.5$, $p<0.001$]. Post-hoc tests with a Sidak correction showed that the clinical map was rated more highly than the SG map [$p=0.019$, $r=0.76$] and the Greenwood map [$p<0.001$, $r=0.91$], both large effects, but the difference in map sound quality rating between the SG and Greenwood maps was not significantly different [$p=0.206$].

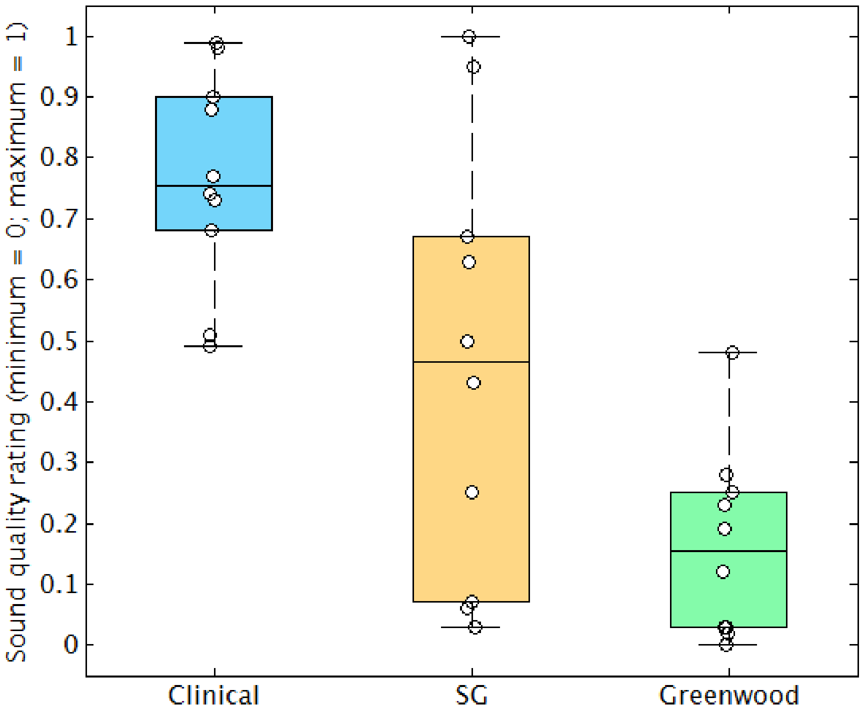


Figure 24 Map quality ratings for the clinical, SG and Greenwood maps as reported on the map quality questionnaire at the end of each trial period. For information relating to the interpretation of boxplots, see section 3.2.1.

3.2.4 BKB Sentence Test Scores

BKB sentence scores for the clinical and SG maps were found to be normally distributed but results for the Greenwood map were not normally distributed as there was a floor effect for this map, both before and after acclimatisation. In view of this, the BKB sentence data were transformed using a rationalised arcsine unit (RAU) transform (Studebaker, 1985). Following this, data were normally distributed for all maps. Scores for the two test sessions are shown in Figure 25.

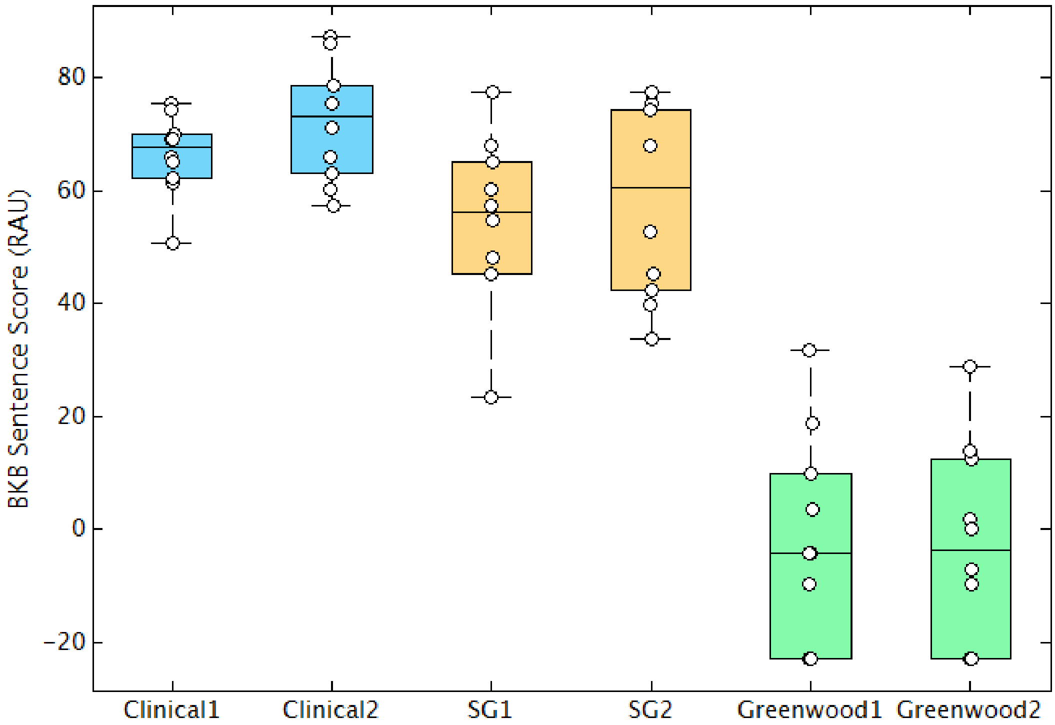


Figure 25 BKB Sentence scores for the two sessions for each map. For information relating to the interpretation of boxplots, see section 3.2.1.

Results for the BKB sentence test were analysed to see if there was any change in score for the two test occasions. Paired t-tests (2-tailed) were performed. No change in sentence perception was shown for any of the maps between the two test intervals [clinical map $t(9)=-2.204$, $p=0.055$, SG map $t(9)=-0.971$, $p=0.357$, Greenwood map $t(9)=0.171$, $p=0.868$]. In view of this result, scores were averaged over the two test sessions for each map for the subsequent analyses. Averaged data are shown in Figure 26.

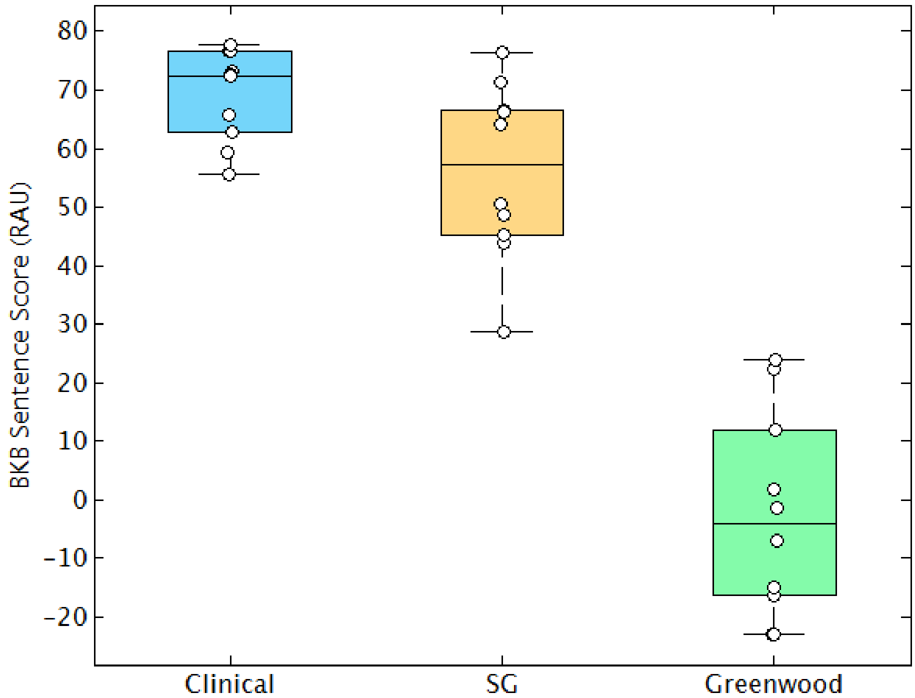


Figure 26 BKB sentence scores for each map averaged over the two test sessions. For information relating to the interpretation of boxplots, see section 3.2.1.

Repeated measures ANCOVA was performed for the transformed BKB sentence scores. The within-subjects factor was the frequency allocation and the co-variates were the estimated insertion angle and the signal to noise ratio used for each participant in the test. ANCOVA confirmed a significant main effect of map frequency allocation [$F(2,14) = 51.3$, $p<0.001$]. There was also a significant interaction between the map frequency allocation and the estimated insertion angle [$F(2,14) = 28.5$, $p<0.001$], whilst there was no interaction between the map frequency allocation and the SNR used in the test [$F(2,14) = 1.13$, $p=0.351$]. There was no independent effect of estimated insertion angle [$F(1,7) = 0.127$, $p=0.732$] or SNR used [$F(1,7) = 1.85$, $p=0.216$]. The fact that there was no effect of SNR used, suggests that participants experienced similar changes in sentence perception ability as a result of adjustment of the frequency allocation, even though performance on the test was variable with the clinical map and they were tested with different amounts of background noise. However, as there may have been a relationship between the estimated insertion angle and the SNR used in the test, linear regression was performed with the estimated insertion angle as the independent variable and the SNR as the dependent variable (both of these variables were normally distributed). No significant correlation was found [$r=0.098$; $p=0.787$].

Post-hoc tests with a Sidak correction, following the ANCOVA, showed that performance was better with the clinical map than with the SG map [p = 0.014, r=0.42], a medium effect and also the Greenwood map [p<0.001, r=0.95], a large effect. Performance with the SG map was better than performance with the Greenwood map [p<0.001, r=0.97].

3.2.4.1 Effect of Insertion Angle on BKB Test Scores

The interaction between the estimated insertion angle and sentence score was strongest for the Greenwood map [r=0.838, p=0.002] but also significant for the SG map [r=-0.700, p=0.024], both large effects, although the SG map correlation would not have been found to be significant if a Bonferroni correction for three correlations had been applied. There was no correlation between the estimated insertion angle and BKB score with the clinical map, as expected [r=-0.308, p=0.387]. For the SG and Greenwood maps, the direction of the correlation reflected the magnitude of change in frequency-to-electrode mapping, which was experienced by participants when trying these maps, as shown in Figure 27.

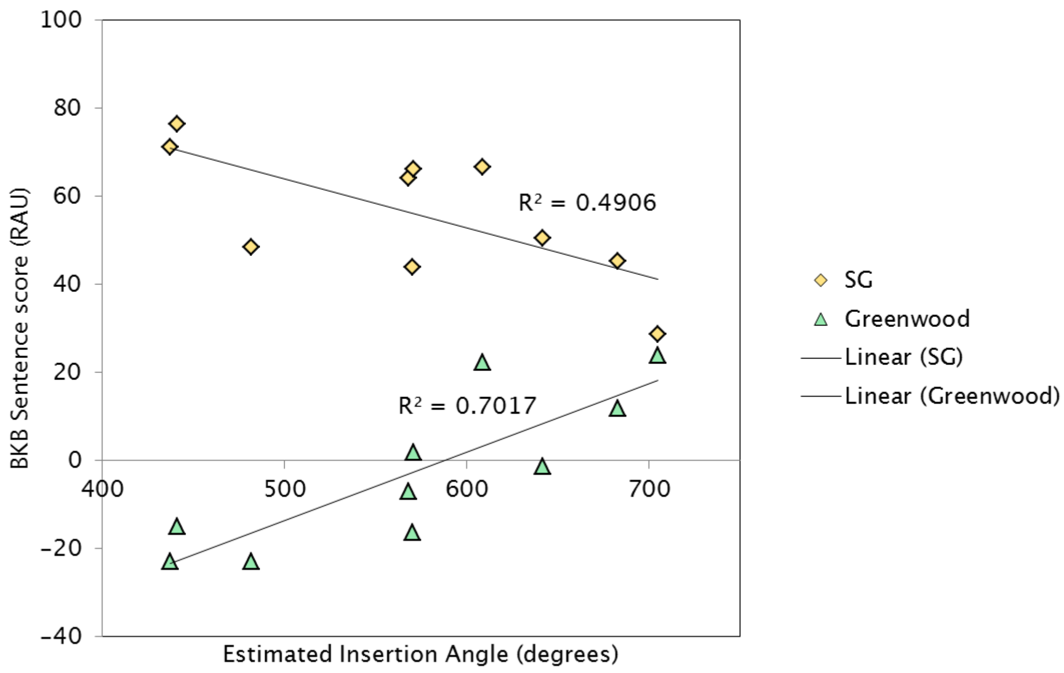


Figure 27 Scatter plots showing correlations between estimated insertion angle and BKB score for the Greenwood and SG maps

3.2.4.2 BKB Sentence Test Scores for Individual Participants

Critical differences on the BKB sentence test, as described by (Martin, 1997), were used to determine significant changes in test score for individual participants.

Critical differences were found prior to the RAU transform. They vary from 15% in the middle of the range to smaller values at the extreme ends (e.g. if the score for the first test of 32 sentences is 41%, a score of 56% will be significantly higher; if the score for the first test of 32 sentences is 93% correct, a score of 99% correct will be significantly higher). It was found that all participants performed worse with the Greenwood map than with their clinical map, whilst four performed worse with their SG map and six performed at a similar level, as shown in Figure 28.

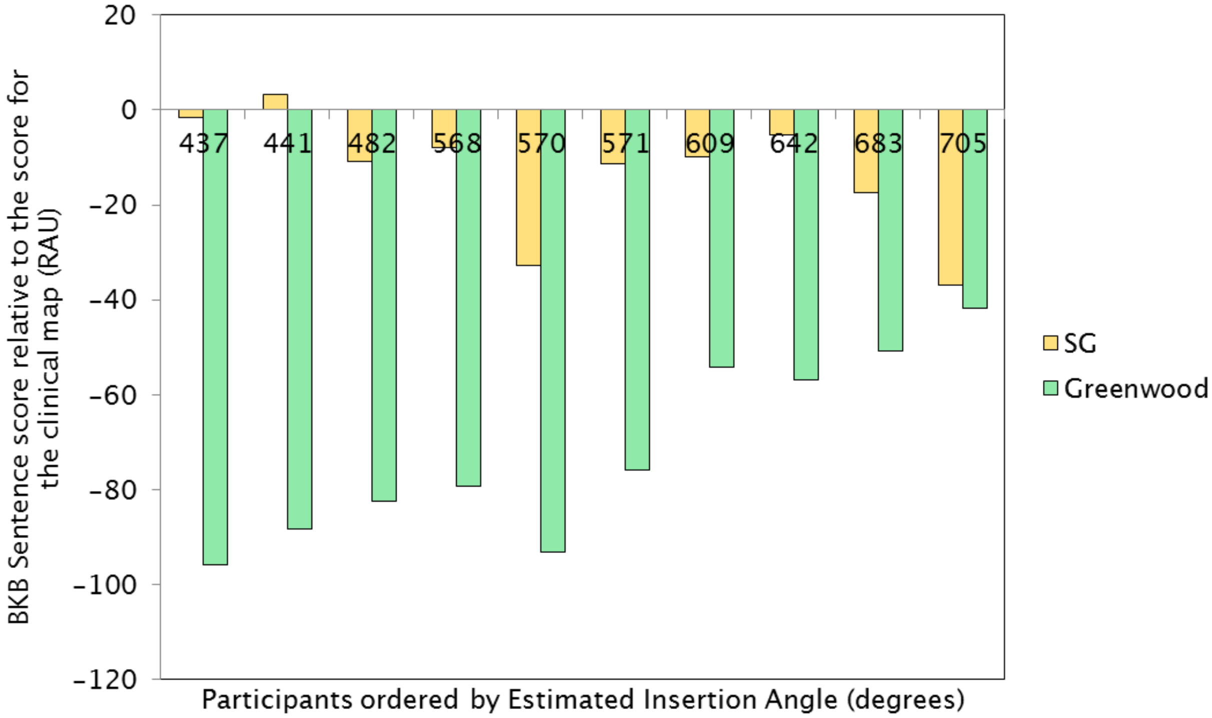


Figure 28 Individual participants' scores on the BKB Sentence test, relative to their score with the Clinical map

3.2.5 Vowel Identification Test Scores

Vowel tests scores with the different maps are shown in Figure 29.

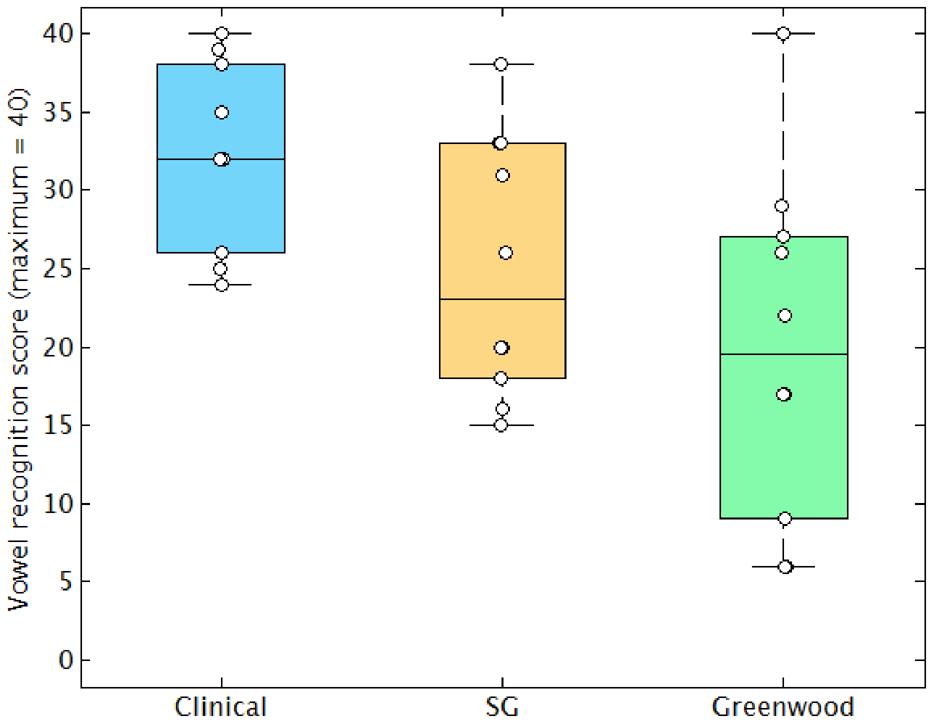


Figure 29 Vowel perception scores for the different frequency allocations. For information relating to the interpretation of boxplots, see section 3.2.1.

Test scores were normally distributed for all the different frequency allocations (Shapiro-Wilk $p>0.05$). ANCOVA was performed: the within-subjects factor was the frequency allocation and the co-variate was the estimated insertion angle. A significant main effect of frequency allocation was found [$F(2,16)=25.5$, $p<0.001$]. There was also a significant interaction between the frequency allocation and the estimated insertion angle [$F(2,16)=21.8$, $p<0.001$]. There was no independent effect of estimated insertion angle [$F(1,8)=0.649$, $p=0.444$]. Post-hoc tests with a Sidak correction showed that the SG and Greenwood maps gave poorer scores than the clinical map [$p=0.001$, $r=0.58$] with the SG map (a large effect) and [$p=0.001$, $r=0.89$] with the Greenwood map (again a large effect). The SG and Greenwood maps did not give significantly different scores from each other [$p=0.088$].

3.2.5.1 Effect of Insertion Angle on Vowel Test Scores

A significant correlation was found between the estimated insertion angle and scores for the Greenwood allocation [$r=0.852$, $p<0.01$, 2-tailed]; participants with deeper insertion angles performed better with this allocation than those with shallow insertions, as shown in Figure 30. No significant correlations were found between the estimated insertion angle and scores with the other frequency allocations [p=0.769 with the clinical map; p=0.108 with the SG map].

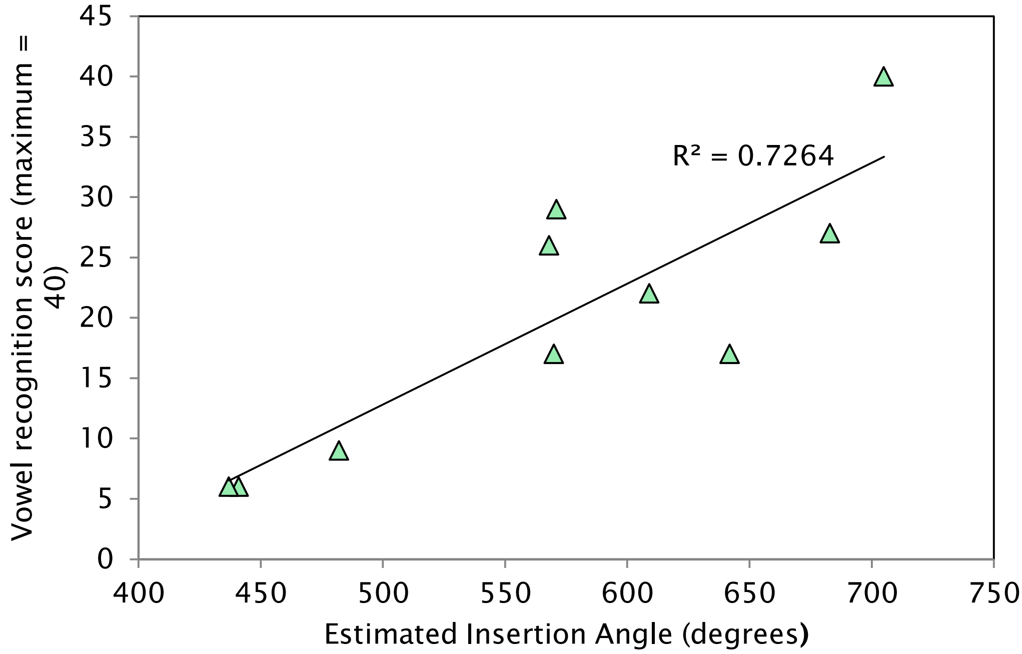


Figure 30 Correlation between estimated insertion angle and vowel recognition score for the Greenwood map

3.2.6 Piano Discrimination Test Scores

Piano test scores with the different maps are shown for the two test intervals with each map in Figure 31.

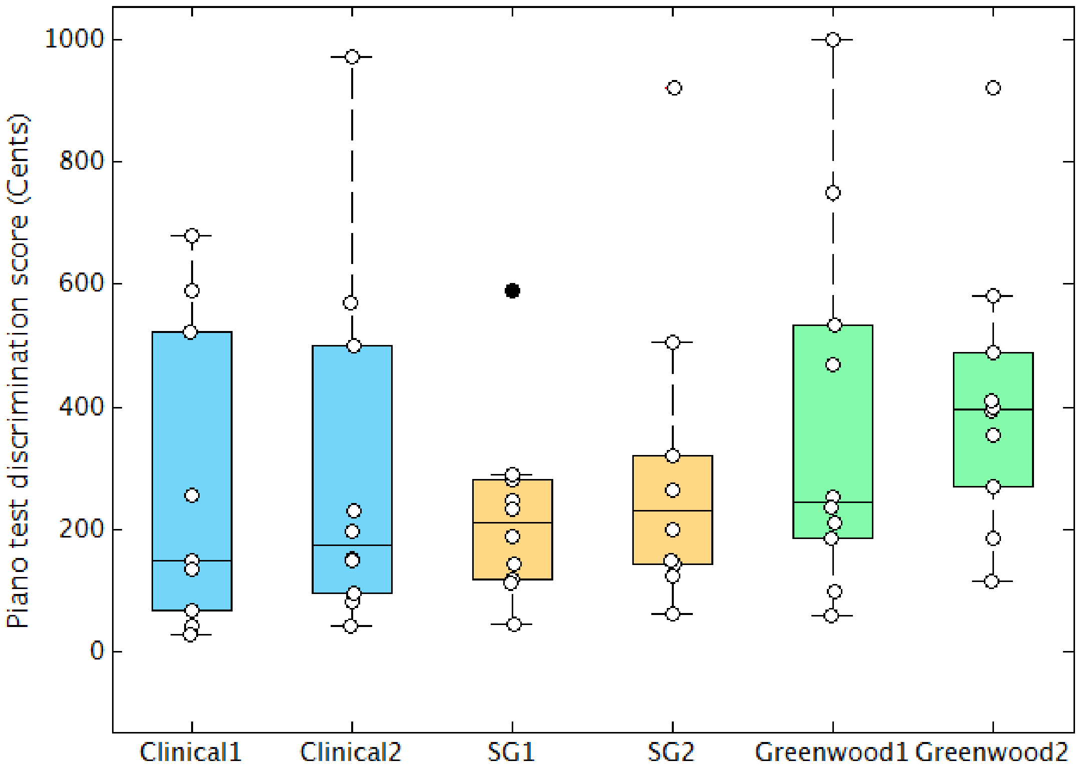


Figure 31 Piano test scores for the first and second test sessions with the different maps. For information relating to the interpretation of boxplots, see section 3.2.1. In this case, a lower score represents better performance.

Only the Greenwood scores were found to be normally distributed for the piano test (Shapiro-Wilk $p>0.05$). Wilcoxon's signed ranks test was used to investigate the effect of test session on scores with the different maps. No significant difference in piano test scores was observed between the two test sessions for any of the maps [$Z = -0.357$, -0.764 and -0.866, $p>0.05$ for the clinical, SG and Greenwood maps respectively]. Scores were averaged over the two test sessions, but scores for the clinical map were still not normally distributed. Scores averaged over the two tests for each map are shown in Figure 32.

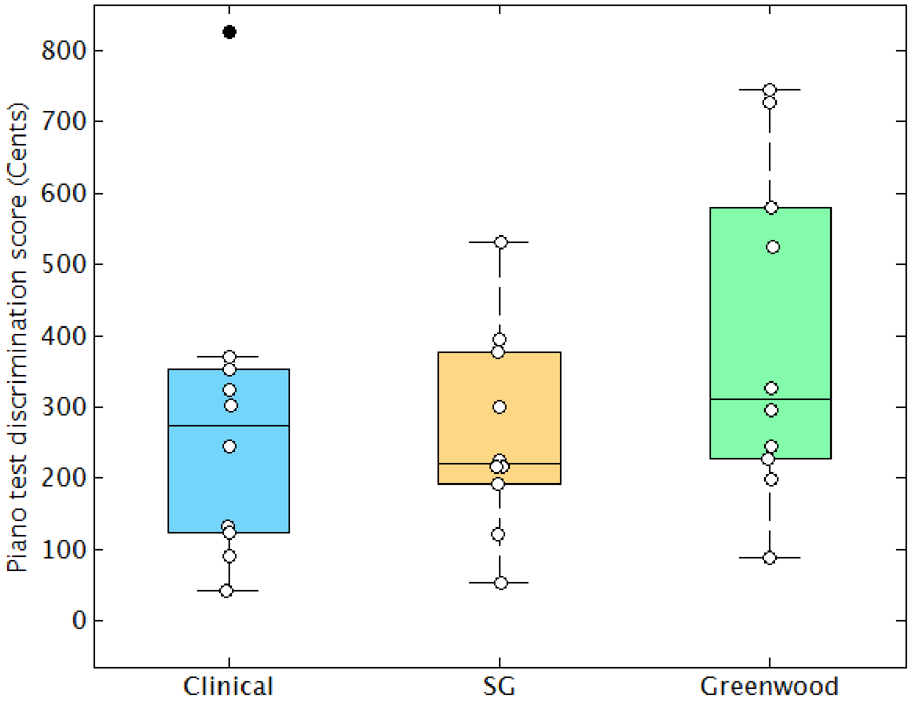


Figure 32 Piano test scores averaged over the two test sessions with the different maps. For information relating to the interpretation of boxplots, see section 3.2.1. In this case a lower score represents better performance.

Piano test scores averaged over the two sessions were investigated using Friedman's test. No significant effect of map was observed [$\chi^2(2,10) = 5.00$, p=0.082].

3.2.7 Electrode Discrimination Test Scores

Electrode discrimination results are shown in Figure 33 for electrodes one to ten, which were active for all participants. Friedman's test confirmed a significant effect of electrode pair on discrimination scores [$\chi^2(8)=24.1$, $p=0.002$]. Wilcoxon signed ranks test comparing electrodes E5 and E6, in the middle of the electrode array, with other pairs (no corrections applied) suggested that performance was poorer for E1E2 and E2E3 when compared with E5E6 [$Z=-2.68$, $p=0.007$, $r=-0.60$ (a large effect) and $Z=-2.41$, $p=0.016$, $r=-0.54$, again a large effect]. Had a Bonferroni correction for eight comparisons been applied, neither of these comparisons would have been considered significant, in contradiction of the result of Friedman's test.

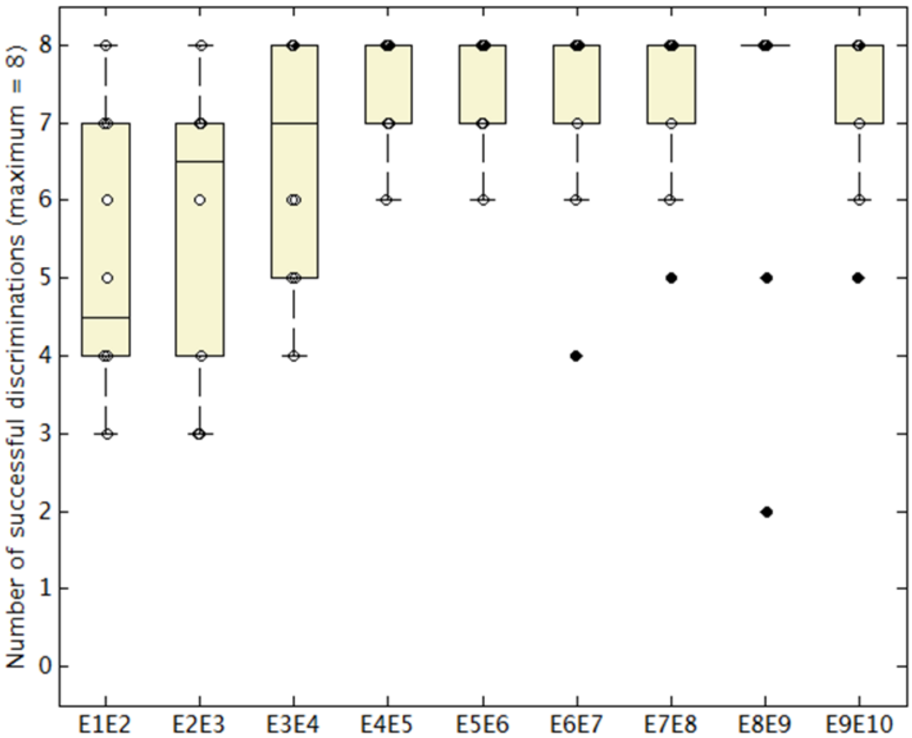


Figure 33 Electrode discrimination results for individual electrode pairs

3.2.8 Interaction between Insertion Angle and Electrode Discrimination

Electrode discrimination was found to be poorer for apical electrodes than for electrodes in the middle of the electrode array. In view of this finding, electrode discrimination was investigated as a function of estimated insertion angle. The mid-way point between each pair was taken as the insertion angle of the pair. Electrode discrimination was found to be poorer for electrodes in the middle turn (insertion angle for the mid-way point of the pair > 360˚), than those in the basal turn [Mann-Whitney U=441.5, p<0.001, r=-0.47, a medium effect], as shown in Figure 34.

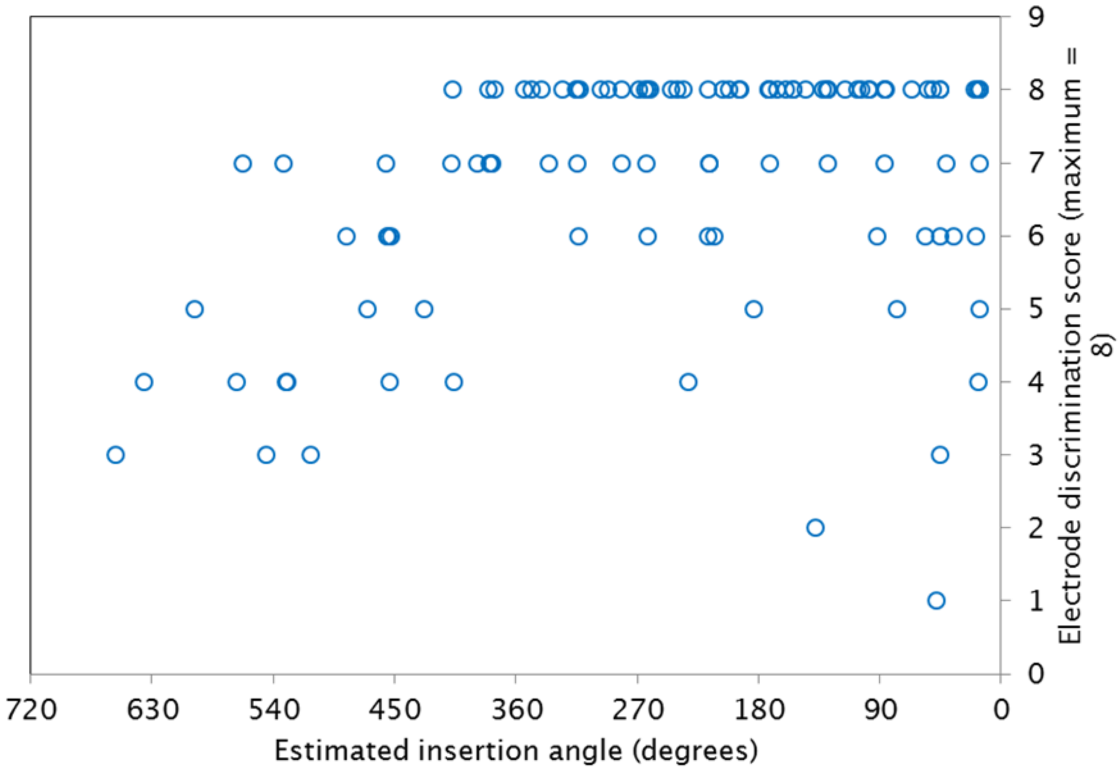


Figure 34 Electrode discrimination score for individual electrode pairs as a function of insertion angle

In addition, a significant correlation was found between the electrode discrimination score for electrode pairs E1E2 and E2E3 (maximum total score = 16) and the estimated insertion angle (for E1) [r=-0.814, p=0.004, a large effect], as shown in Figure 35. No significant correlation was found between the estimated insertion angle and electrode discrimination scores for middle and basal electrodes [Spearman's rho p>0.05 for electrode pairs E5E6 and E6E7 and also E8E9 and

E9E10].

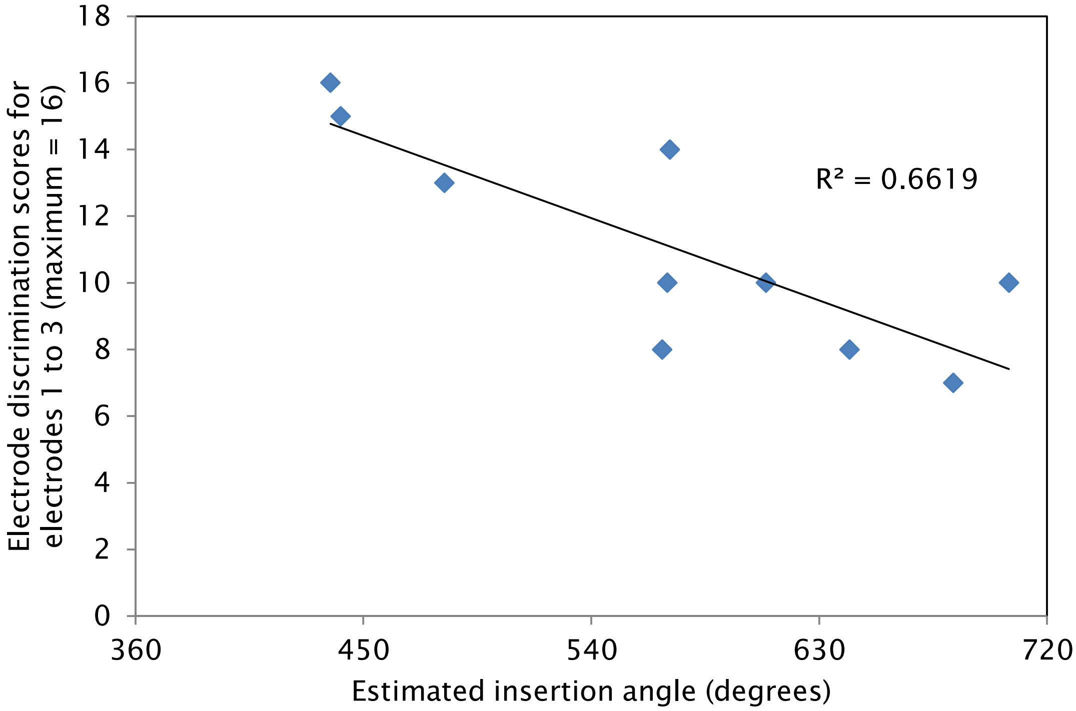


Figure 35 Correlation between estimated insertion angle and electrode discrimination score for the two most apical electrode pairs

3.3 Discussion

3.3.1 Effect of Frequency Allocation

The results of the present study are consistent with the idea that speech perception by CI users is sensitive to changes of frequency allocation. In order to achieve the optimum performance, the frequency allocation should be adjusted to the most appropriate setting. The clinical map gave the best results of the three maps tested for this group of participants; there is a need to consider whether this represents an optimal map for both the whole group and for individual CI users. As it includes all the speech frequency range, it represents a good starting point for speech perception. However, some participants in the experiment had poor electrode discrimination for their apical electrodes. It is possible that the clinical map may not have been ideal for these participants, as a larger proportion of the frequency range is allocated to these electrodes than to more basal electrodes. There is also a need to consider whether the alternative maps offered poorer performance due to lack of acclimatisation, issues related to mapping (e.g. loss of electrodes or frequency range) or issues related to pitch perception (e.g. poor discrimination).

3.3.2 Measurements of Insertion angle and Accuracy of Fitting of the Maps

For participants in the main experiment, there was a greater range of insertion angles (438 to 699°) than for the X-ray review (561to 701°). The assumed proportions of cochlear length for the electrode arrays included in the main experiment may have deviated to some extent from the proportion of the total insertion angle found from the reviewed X-rays, particularly for those with the same number of active electrodes, but a smaller or larger proportion of them in the basal turn. The mean insertion angle in the main experiment was 571° compared to 645° for the review. However, for a shallow insertion of 440°, an exponential function was a good approximation to the relationship between electrode number and lower frequency boundary for both the Greenwood and SG maps (R^2=0.9995 for the SG map and R^2=0.9991 for the Greenwood map). For the deepest estimated insertion of 706°, an exponential function was not such a good fit to the relationship between electrode number and lower frequency boundary (R^2=0.994 for the SG map and R^2=0.996 for the Greenwood map) but was sufficient to resemble an exponential function. So, the frequency spacing for the SG and

Greenwood maps was considered to be acceptable. Similarly, estimated insertion angles were found to vary from the measured insertion angles by 6˚ on average, which is a small amount relative to the total insertion angle. So, whilst the method used for calculating lower frequency boundaries for electrodes in this experiment involved estimation of insertion angles from plain X-rays, which was less than ideal, the resulting frequency allocations had appropriate shapes and were considered to be reasonably representative of the Greenwood function and covered an appropriate area of the cochlea for the SG function.

3.3.3 Use of the Alternative Maps

For both the Greenwood and SG maps, the limited time use reported by participants in the study is striking. This suggests that CI users find adjustment to a different frequency allocation a difficult step. Use of the Greenwood map was particularly limited and this suggests that CI users are not willing to use a map which is perceived to be of significantly poorer quality than their clinical map when they first try it, even if they have been told that it will take some time to get used to it.

3.3.4 Performance with Different Maps on the BKB Sentence Test

An interesting finding was that performance on the BKB sentence test was correlated in opposite directions for the SG and Greenwood maps. Those with deeper insertions performed better than those with shallow insertions with the Greenwood map, whilst those with shallow insertions performed better than those with deep insertions with the SG map, although to a lesser degree. This finding is in keeping with the amount of adjustment made to participants' maps. Mapping to the SG map resulted in basal shift for the majority of participants whilst mapping to the Greenwood function resulted in apical shift for all participants. Performance was best with the clinical map. This suggests that participants had acclimatised to their clinical maps and the strangeness of the other maps resulted in poorer performance.

3.3.5 Performance with the SG Map

The SG map yielded poorer performance than the clinical map for the group, for vowel and sentence perception. However, the two participants with the shallowest insertions (P5 and P10), chose to continue with the SG map at the end of study, as they preferred its sound quality over that of the clinical map, whilst having similar performance with both maps. For these two participants the frequency shift from the clinical map was minimal and hence the main differences between the default and SG maps were that the most basal electrode was deactivated in the SG map and the relative widths of the frequency bands were different. The SG map has approximately logarithmic frequency spacing whereas the default map is a fourth order polynomial function, which includes more low frequencies than the SG map for these two participants.

3.3.6 Performance with the Greenwood Map

Maps with frequency allocations based on the Greenwood function led to markedly reduced performance for both speech perception tests. It is possible that the Greenwood function may not represent the optimal frequency mapping for CI users for other reasons than frequency shift, although the Greenwood map had more frequency shift on average from participants' clinical maps than the SG map. For those with shallow insertions, there was an additional issue of a significant loss of frequency range. Performance was predicted by the estimated insertion angle for both the sentence and vowel tests with this map; those with deeper insertions (and therefore less frequency shift and loss of frequency range) performed better than those with shallow insertions. The Greenwood allocation also resulted in a reduction in the number of active electrodes, a reduction in the number of fine structure channels for the majority of participants and an increase in the stimulation rate. The loss of channels offering fine structure cues was due to the reduced frequency range at the apical end for those with shallow insertions. In addition, for some participants, the processor's filter settings did not allow the lower frequency boundary to be programmed as intended, especially for the most basal electrode. Some or all of these factors may have contributed to the poor performance with the Greenwood map, although the loss of electrodes and difficulties with filter settings were similar for the SG map, for which performance was significantly better. A study by Shannon *et al.* (1998) found that shifting of frequency bands had a much greater effect on speech perception than overlap of bands or exact frequency divisions.

3.3.7 Performance on the Vowel Test

Another issue to consider is the extent to which speech sounds could be discriminated with the different maps. The alternative maps used a smaller number of electrodes than the clinical maps and therefore there was a risk of frequency compression for speech sounds. Taking P2 as an example, with a relatively deep estimated insertion of 642°, the first formants for the female speaker in the vowel test ranged from 361 to 1009 Hz and would have been mapped to electrodes three to six for the clinical map, electrodes three to seven for the SG map and electrodes two to four for the Greenwood map. The second formants for the same speaker ranged from 1.22 to 2.63 kHz and would have been mapped to electrodes six to nine for the clinical map, seven to nine for the SG map and five to seven for the Greenwood map. Hence the vowel formants for the female speaker were spread over seven electrodes for the clinical and SG maps but only six electrodes for the Greenwood map. This suggests that in addition to the frequency shift, participants were faced with some loss of discrimination ability for the Greenwood map, as a smaller number of electrodes carried the same information. The SG map may have sounded somewhat distorted in comparison to the clinical map owing to the different spread of formant frequencies across the electrode array.

For P3, with an estimated insertion angle of 570°, the first formants would have been mapped to electrodes three to six for the clinical map, four to six for the SG map and one to four for the Greenwood map. The second formants would have been mapped to electrodes six to nine for the clinical map, seven to eight for the SG map and four to six for the Greenwood map. So, vowel formants were spread across seven electrodes for the clinical map, five electrodes for the SG map and six electrodes for the Greenwood map. The formant frequencies appear to be less well spread over the electrode array for both the alternative maps than for the clinical map for this participant.

For P10, with an estimated insertion angle of only 437°, the first formants would have been mapped to electrodes three to five for the clinical map, two to five for the SG map and electrodes one to two for the Greenwood map, with some first formants missing from the map altogether. The second formants would have been mapped to electrodes six to eight for the clinical map, five to seven for the SG map and three to five for the Greenwood map. So, vowel formants were spread across six electrodes for the clinical and SG maps but only five electrodes for the Greenwood map.

The mean vowel test score was 32/40 for the clinical map, 25/40 for the SG map and 20/40 for the Greenwood map. The very poor results for the three participants with insertion angles <500° on this test suggest that the loss frequency range may have adversely affected performance for these participants with this map.

3.3.8 Electrode Discrimination Abilities

Electrode discrimination was also measured as part of the first experiment and the results showed that electrode discrimination was poor for six out of ten participants at the apical end of the array. This is consistent with the literature (see sections 2.5.3 and 2.5.4) and suggests a further reason as to why the Greenwood map may offer poorer performance than the clinical map. With the clinical map, sounds with frequencies below 500 Hz are mapped to electrodes one to three, where discrimination was poor for some participants. With the Greenwood map, higher frequency sounds are typically mapped to those electrodes. For example, for P2, frequencies from 197 to 744 Hz were mapped to the three most apical electrodes in his case. So some first formant frequencies were mapped to an area of the cochlea where discrimination ability was poorer. Conversely, only sounds up to 224 Hz were mapped to these electrodes with the SG map, so there was a potential advantage of this map.

3.3.9 Performance on the Piano Test

The piano test was unfortunately unable to provide any further insights into sound perception with the three different maps. It may be that all three maps offered similar discrimination opportunities for piano notes, as the large number of harmonics would mean that it was possible to perform the test even with some loss of frequency range. Alternatively, it may be that a significant effect of map would have been found with a larger number of participants. Only a non-parametric test was appropriate as the data were not normally distributed. The *p*-value for this test of 0.082 was not far off statistical significance, so it is possible that with a larger number of participants, an effect might have been seen. The Greenwood map had the numerically poorest scores on the test. The electrode discrimination test results suggest that the Greenwood map would have offered poorer performance for frequency discrimination for some participants, as electrode discrimination was poorer for apical electrodes and important frequencies (the lower harmonics) were moved in the apical direction with the Greenwood map. In addition, there was a loss of frequency range for the Greenwood map, such that the fundamental frequency would have been missing for some stimuli for the test for the participants with shallow insertions. For the three participants with the shallowest insertions, the fundamental frequency would have been missing for the reference stimuli and the majority of the test stimuli.

It may be that difficulties with test itself meant that it was not sufficiently sensitive to difficulties encountered by participants with different maps and hence no effect was observed. One possibility is that some participants found the task too difficult and were unable to perform the task effectively. In fact, some participants obtained scores worse than 600 cents (half an octave) on this test and at times reached the largest possible interval on the test, which does suggest a difficulty with performing the task. There are a number of possible reasons for this.

The first reason is that the stimulus was a complex tone with a limited steady-state phase (sampled piano notes). Whilst piano notes are common in western music, the pitch of the tones may have been more difficult to perceive than the pitch of the pure tones used in the electrode discrimination test.

Secondly, loudness roving of ±3 dB was used in both tests to cover any potential loudness issues but may have added to the difficulty of the tests. In the case of the electrode discrimination task, 3 dB may have been more than was required but the majority of participants still performed well on this task, at least for most electrode pairs. Calibration of the piano test was performed in soundfield, in keeping with the method of presentation of the test and was less accurate than for the electrode discrimination task (see appendix 2). This was consistent with the time-varying nature of the stimuli and soundfield presentation. Less predictable loudness may have contributed to the difficulty of the task.

Thirdly, the test was run adaptively, which would have been less than ideal for those participants who found the test difficult. Adaptive procedures such as the 2-down, 1-up method used in this test are designed for tasks that can be represented by a simple monotonic function and the points tested are relatively evenly spaced around the 50% correct level for tasks with scores between 0 and 100% correct (Levitt, 1971). If individuals' abilities were poor for this task, the procedure may not have run in the intended way.

It was concluded that the piano notes discrimination test was of limited value for this CI frequency allocation experiment.

3.3.10 Fixed Frequency to Position Maps

Adjustment of the frequency allocation had a marked effect on speech perception for participants in this study. Mapping to the estimated normal acoustic tonotopic frequency map resulted in poor performance for all participants, whilst a compressed map limited to the area likely to contain SG cells resulted in poorer performance than for the clinical (default) map, for the majority of participants.

The fact that performance was correlated with insertion angle for the sentence test results suggests that participants in the study had already successfully acclimatised to the frequency allocation in their clinical maps, which was mostly the default frequency allocation. Vowel test scores were also correlated with insertion angle for the Greenwood map: those with the largest map changes, relative to their clinical map, scored lower than those for whom the adjustments had been more limited. The sentence and vowel test findings are in agreement with each other. The lack of use of the alternative maps and sound quality ratings are consistent with the idea that frequency maps that were similar to the map which they were familiar with were perceived as better. If the map changes could have been introduced in a step-wise manner, rather than all at the same time, this may have been easier for participants, as suggested by Svirsky *et al.* (2015). However, as there were other factors involved which were likely to have affected performance, especially deactivation of electrodes and loss of frequency range with the Greenwood map, further data would be necessary to confirm to what extent performance was dependent on acclimatisation or other issues. One possibility, which would help to ascertain the influence of loss frequency range on the results, would be to retest participants with deep insertions with a Greenwood allocation but with some low frequencies removed. Previous studies by Başkent and Shannon (2004, 2005) suggest that loss of frequency range at the apical end can be tolerated more easily than frequency shift.

It is possible that the results may have been different if the experiment had been performed before participants had acclimatised to their clinical maps, or if participants with lower scores had been invited to take part. As acclimatisation appears to have been successful for study participants, the potential benefit of the Greenwood map was not realised. Neither did the SG map offer improved performance when compared to the clinical map, even for those with poor pitch perception at the apical end of the array.

One limitation of the Greenwood and SG maps was that the number of active electrodes was limited at the basal end, due to basal electrodes having frequencies assigned to them which were beyond the range of the CI. An issue for fixed frequency position maps is that there is no opportunity to adjust the position of the electrodes post-operatively, even if they are not in suitable positions to be used in the map.

It was decided that assigning frequencies to fixed positions in the cochlea as a method of frequency allocation should not be pursued further for the purposes of this study. The data collected and analysed for experiment 1 part 1 were insufficient to answer the research questions posed in section 2.11.1, as no actual improvements in performance were realised. However, as variations in pitch perception and insertion angle were observed, this suggested that it still might be possible to improve performance by adjusting the frequency allocation for individual CI users.

The next part of the study would focus on the issue of poor pitch perception at the apical end of the array, which affected six of the ten participants in the experiment. The intention was to devise a map which would result in benefit for at least a proportion of the participants and thereby enable the research questions posed in section 2.11.1 to be answered. A new map would be designed to improve performance for those with poor pitch perception at the apical end of the array, without prejudicing those with good pitch perception in this area. This would be accomplished through the use of some basal shift and by reducing the allocation of frequencies to the apical electrodes. Frequency compression, which results from deactivation of electrodes, would be avoided and spectral shift would be limited, as would truncation of the frequency range.

3.3.11 Rationale for Experiment 1 part 2

A new frequency allocation was devised, which had the same shape and frequency range for all participants. It incorporated some basal shift when compared to the default allocation, to focus stimulation away from the area of potentially poor pitch perception at the apical end. This was achieved by using logarithmic frequency spacing combined with a limited amount of truncation of the frequency range at both ends of the array. It was anticipated that the use of uniform frequency spacing would reduce potential problems with the processor's filters not being able to deliver the desired frequencies, which occurred in the first part of the experiment. To avoid reducing frequency resolution for the most important speech frequencies, in the middle of the frequency range, all available electrodes were activated and the frequency range was reduced to some extent. Loss of fine structure cues was avoided by using all available electrodes and ensuring that truncation of the frequency range at the apical end was limited. Hence the new map would not suffer from the same limitations as the Greenwood and SG maps.

Chapter 4: Experiment 1 Part 2: Reduced Frequency Range Map for CI Users with Reduced Bandwidth for Apical Electrodes

4.1 Methods

An experiment was performed to compare performance between participants' clinical maps and an alternative map, known as 'Reduced Frequency Range map' (RFR). Participants who took part in the first part of experiment 1 were invited to try this further alternative map in the fourth session of the experiment. Additional consent was sought and received from the Research Ethics Committee (via a substantial amendment) prior to the data collection. It was subsequently requested from and given by all participants who had taken part in experiment 1 part 1. Performance was measured with the RFR map without any take-home experience.

4.1.1 Frequency Allocation

The RFR map had logarithmic frequency spacing, used all available electrodes and included the third octave bands with centre frequencies from 200 to 5000 Hz, giving it a frequency range of 178 to 5612 Hz. A comparison of the RFR and default frequency allocations is shown in Figure 36. The use of this frequency range ensured that the most important speech frequencies were presented to participants (see section 2.6.3 for further details of important speech frequencies).

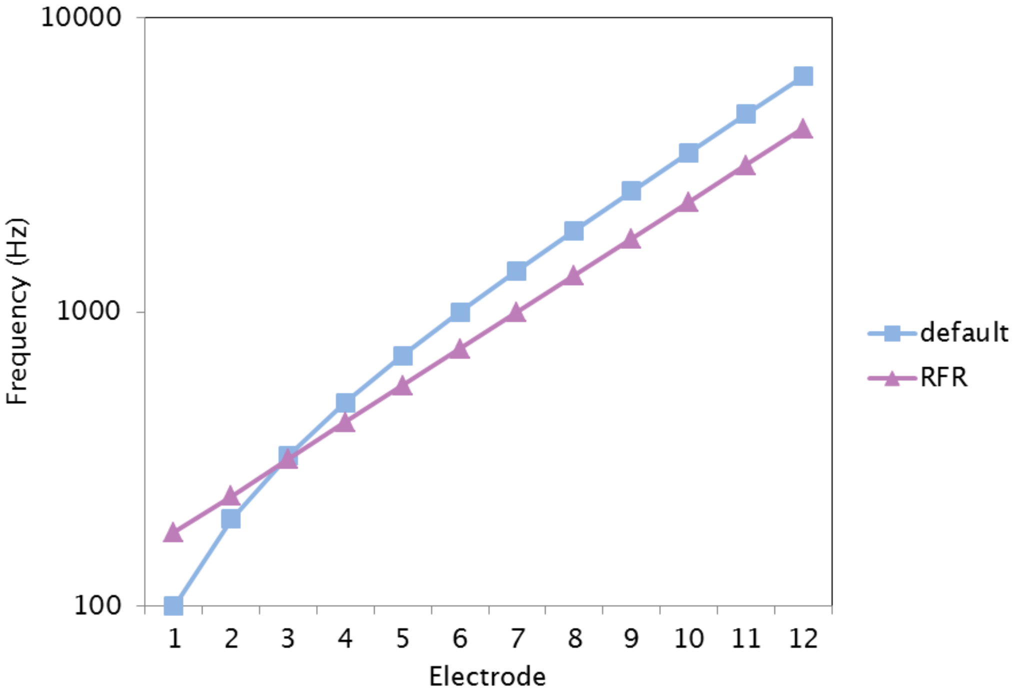


Figure 36 Lower frequency boundaries for the default and RFR frequency allocations

4.1.2 Assessments

The same assessments were used in part 2 of the experiment as in part 1, with the exception of the map quality questionnaire. This was not used in part 2 of the experiment, as participants were not given any take-home experience with the RFR map. Further details of the assessments used (BKB sentence test, vowel identification test and piano notes discrimination test) can be found in section 3.1.6.

4.2 Results

4.2.1 Statistical Analysis

As participants performed the tests with the RFR map without take-home experience, scores with the RFR map were compared with scores with the clinical map prior to take-home experience.

Statistical analysis was performed using *t*-tests to compare between two conditions, where data were normally distributed. Where data were not normally distributed, Wilcoxon's signed ranks test was used.

4.2.2 BKB Sentence Scores with the Clinical and RFR Maps

Scores with the clinical map, at the first test session, and RFR map were both normally distributed. These were compared using a paired samples *t*-test (2-tailed). No significant difference in scores across the group was observed [$t(9)=0.170$, $p=0.868$]. Results are shown in Figure 37.

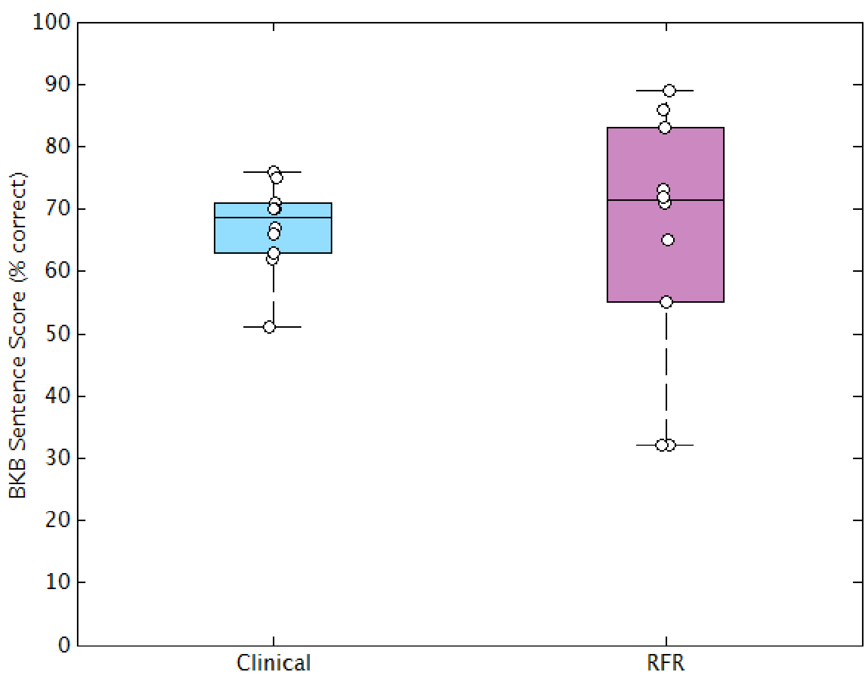


Figure 37 BKB Sentence Test Scores with the Clinical map (first test) and RFR map. For information relating to the interpretation of boxplots, see section 3.2.1.

Three participants (P2, P9 and P12) showed individual improvement on the BKB sentence test with the RFR map when compared with their clinical map; these improvements equalled or exceeded the critical differences for the test, given by Martin (1997). Critical difference values are highest for scores close to 50% correct, with a maximum value of 15%. However, three participants also performed significantly worse with this map (P5, P6 and P11). Comparisons between the clinical map and the other maps for individual participants are shown in Figure 38. These results are given as percent correct, as scores with both maps were normally distributed.

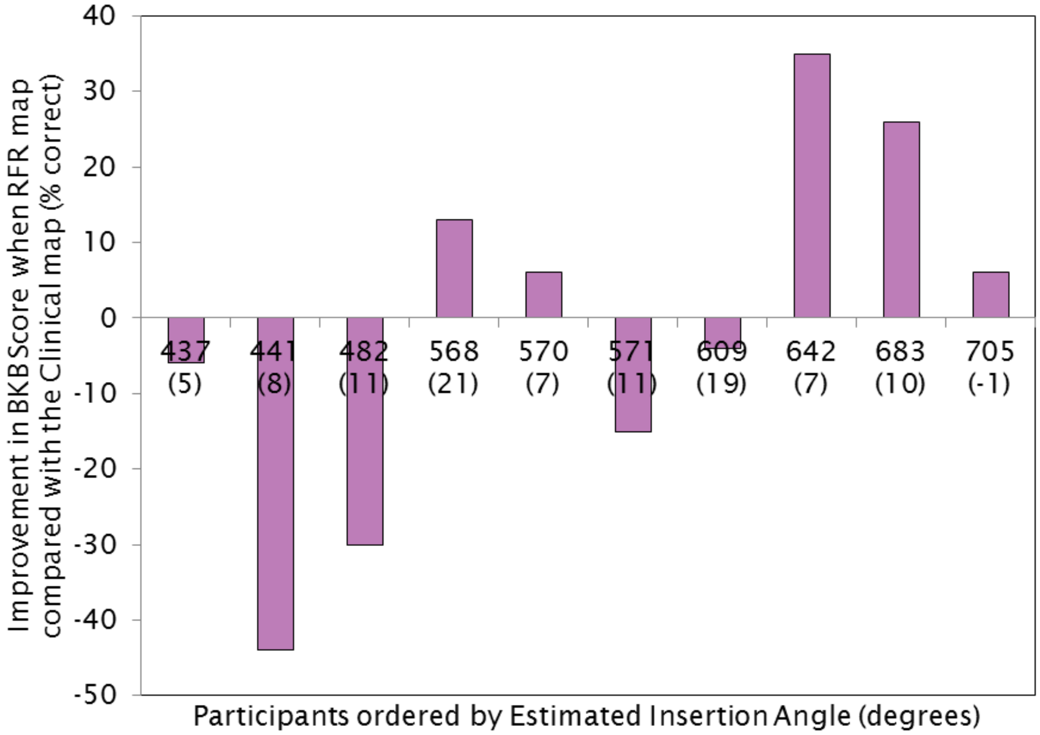


Figure 38 Individual BKB sentence scores when compared to the clinical map. The SNR used in each test is shown in brackets below the estimated insertion angle.

4.2.3 Vowel Test Scores with the Clinical and RFR Maps

Vowel test scores with the clinical and RFR maps were also normally distributed. Vowel test scores for the group with the two maps are shown in Figure 39.

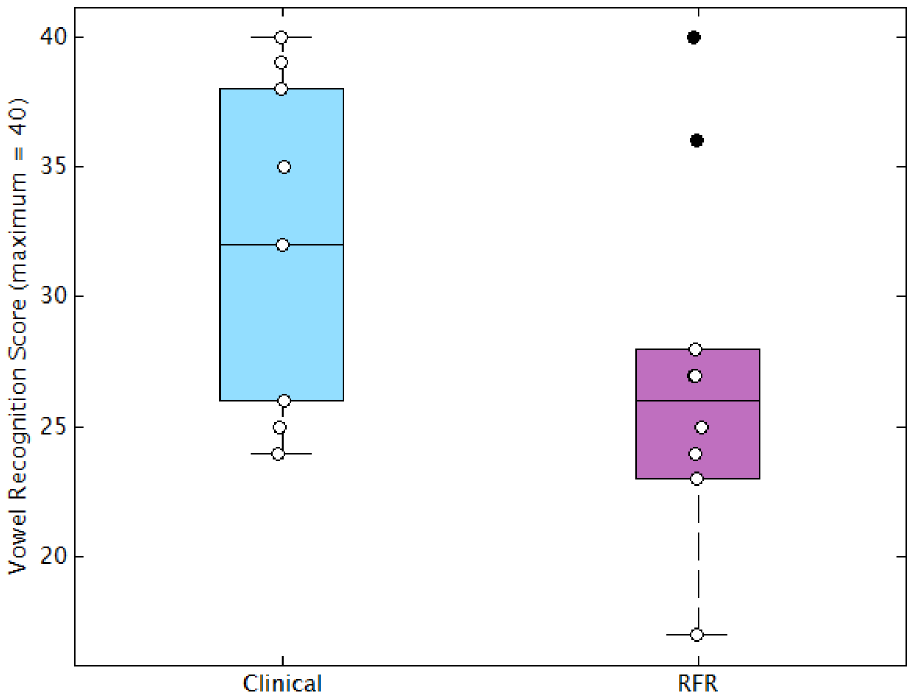


Figure 39 Vowel test scores with the clinical and RFR maps. For information relating to the interpretation of boxplots, see section 3.2.1.

Vowel test scores for these maps were investigated using a paired samples *t*-test (2-tailed). A significant effect of map was found [$t(9) = 2.78$, p=0.022, r=0.68, a large effect], indicating better performance with the clinical map than the RFR map over the group.

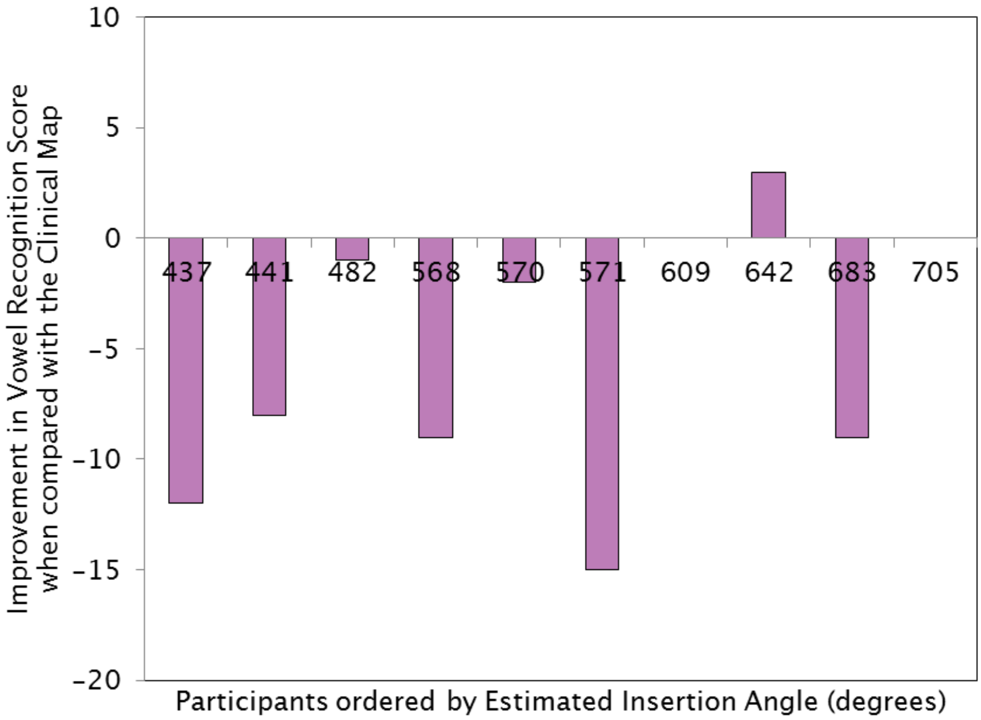


Figure 40 Individual improvement in vowel perception scores with the RFR map compared to scores with the clinical map

It can be seen in Figure 40 that all participants bar one scored worse on the vowel test with the RFR map. The participant who obtained a better score with the RFR map also obtained the most benefit from the RFR map for the BKB sentence test.

4.2.4 Piano Test Scores with the Clinical and RFR Maps

Piano test scores with the clinical map, for the first test and the RFR map are shown in Figure 41.

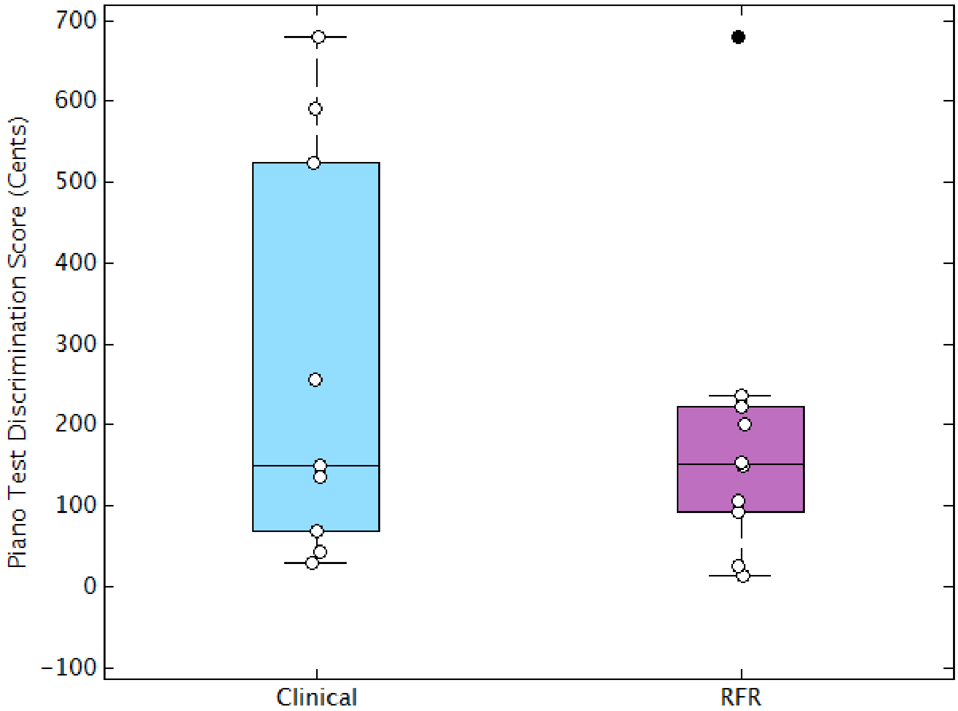


Figure 41 Piano test scores with the clinical and RFR maps. For information relating to the interpretation of boxplots, see section 3.2.1. In this case, a lower score represents better performance.

Scores were not normally distributed for either map. Hence, they were compared using Wilcoxon's Signed Ranks Test. No significant effect was found [Z=-0.663, p=0.508].

4.3 Discussion

The RFR map gave mixed results for the sentence test, with three participants obtaining significantly better scores with this map, using the critical differences published by Martin (1997), whilst the remainder either obtained similar or worse scores than with their clinical map. This is an interesting finding, as all participants experienced a similar amount of frequency shift when listening to this map, in comparison to the clinical map. All RFR maps were also expanded maps in comparison with the clinical maps. If the improvement was due to an improvement in the resolution of important speech sounds, it is uncertain why the benefit was only received by a minority of participants.

A possible explanation for the variable results with the RFR map is that the reduction in frequency range assigned to the apical electrodes might have been more important for some participants than others. The reduction in frequency range was most marked for electrodes one and two. Electrode discrimination was found to be poor for some participants at the apical end of the array. Figure 42 below shows the electrode discrimination profiles for the three participants who obtained improved BKB sentence scores with the RFR map and the three whose performance was poorer with the RFR map. Those who improved with the RFR map all demonstrated poor electrode discrimination for their apical electrodes (chance score = 2.7). Those who performed worse with the RFR map had electrode discrimination scores for their apical electrodes which were significantly above chance (score for eight trials>5.3). Performance for basal electrodes was variable in both groups. The two participants who obtained most benefit from the RFR map both had deep insertions (682 and 642°); the third had a moderately deep insertion (568°). Conversely, two of the three participants who performed worse with this map had shallow insertions (441 and 482°); the third had a moderately deep insertion (571°). Improvements in BKB score as a function of estimated insertion angle are shown in Figure 43 and as a function of discrimination scores for apical electrodes in Figure 44.

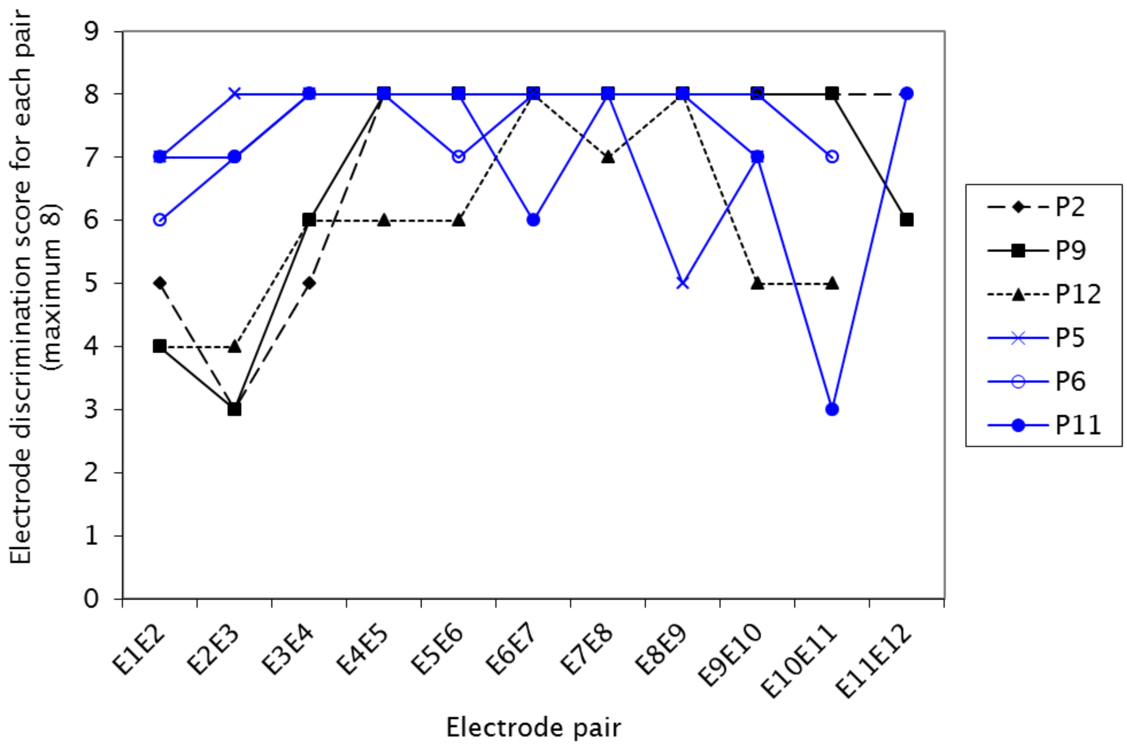


Figure 42 Electrode discrimination scores for those whose score with the RFR and clinical maps was significantly different on the BKB sentence test. Participants with improved performance with the RFR map are shown in black, those with poorer performance in blue.

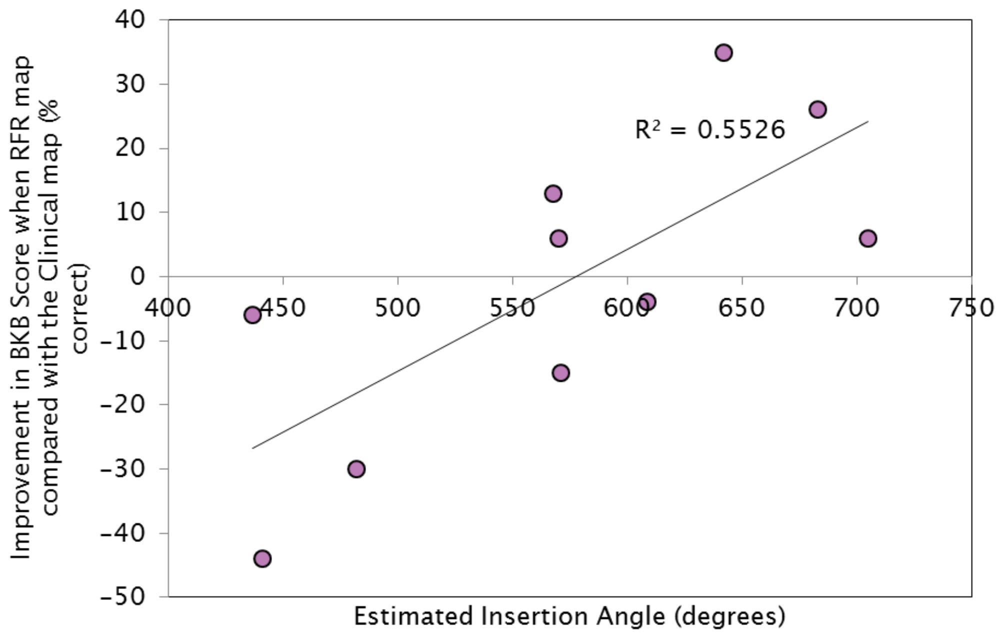


Figure 43 Improvement in BKB score with the RFR map as a function of estimated insertion angle

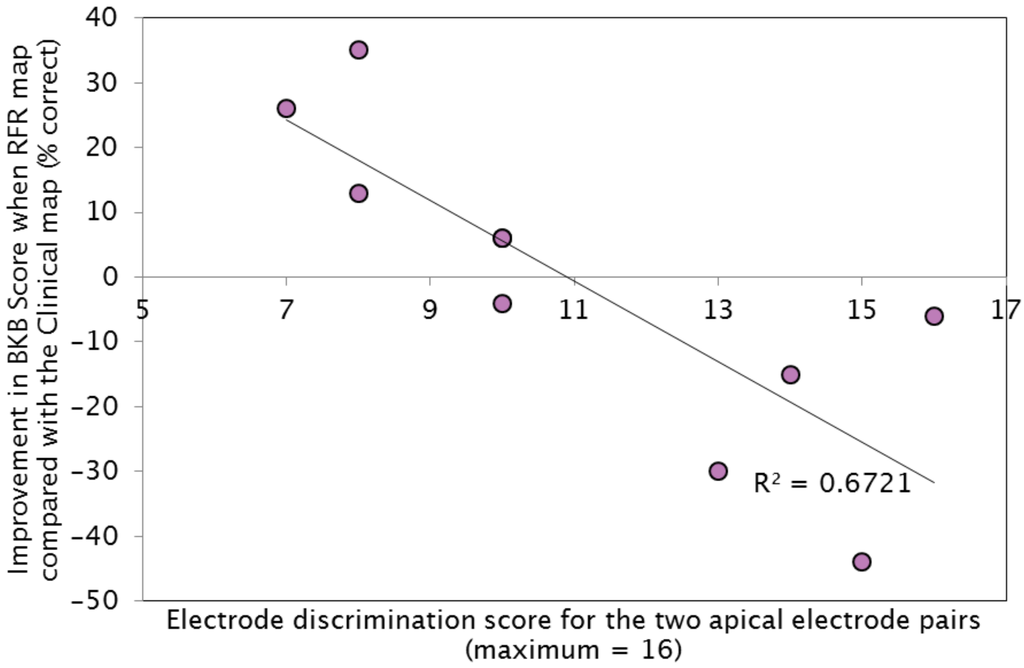


Figure 44 Improvement in score with the RFR map as a function of electrode discrimination score for the two most apical electrode pairs

It may be that the reduced frequency range allocated to the apical electrodes in the RFR map was important in cases of poor discrimination for apical electrodes, consistent with the findings of Gani *et al*. (2007) who showed improved speech perception when apical electrodes were deactivated, in cases with deep insertions and pitch confusions at the apical end. If there is an overlap between the populations of neurons which are stimulated by the apical electrodes, a reduction in the frequency range assigned to each electrode may avoid the situation where these cells are being excited more often than intended. The speech intelligibility index (ANSI, 1997) suggests that the part of the frequency range which is not included in the RFR map at the apical end (100 to 177 Hz) is of limited importance for speech intelligibility, and is therefore unlikely to be missed, although those frequencies still carry significant energy.

Another possibility for the improvement with the RFR map is that slightly higher frequency sounds which are important for speech perception (e.g. 400 to 800 Hz) had been shifted in the basal direction to an area of the cochlea with better discrimination ability. These frequencies were assigned to electrodes three to six in the RFR map, compared to electrodes three to five in the clinical map, for those with twelve active electrodes. The majority of frequencies between 400 and 500 Hz were allocated to electrode three in the clinical map, compared to electrode four in the RFR map.

Interestingly, whilst the RFR map offered mixed results for sentence perception over the group, performance was worse than for the clinical map for vowel perception. The poorer results with the RFR map for the vowel test are likely to be due to the frequency shift and lack of time to acclimatise to it. With the Greenwood and SG maps, other factors such as the loss of frequency range and loss of electrodes may have affected performance on the vowel test but this is not the case with the RFR map, due to the fact that no electrodes were lost and the frequency range covered the most important frequencies for vowel perception. Even so, some participants were more affected by the frequency shift than others, as can be seen in Figure 40.

It is interesting to consider why there was an improvement for two participants on the sentence test whilst there was no improvement or worse performance on the vowel test with the RFR map, when compared to the clinical map. There are two possible explanations for this. Tokens in the vowel test were spoken by a female whilst sentences in the BKB sentence test were spoken by a male speaker. The formant frequencies for the vowel sounds from the words 'head', 'had' and 'heard', which are included in both tests, were 25% higher on average for the female speaker than the male speaker. Whilst vowel tokens would have been allocated to electrodes three to nine for the female speaker for the clinical map, the same vowel tokens would have been allocated to more apical electrodes (possibly electrodes two to eight) for the male speaker. So, potentially poor discrimination had limited effect on the perception of vowels with the clinical map for the female speaker, as the sounds were not allocated to electrodes E1 or E2, where discrimination was poorest.

A second possible reason why an improvement was seen on the sentence test with the RFR map but not on the vowel test for two participants was that the sentence test was performed in noise. The apical electrodes would have been stimulated as a result of the background noise, which may have interfered with perception of the speech. For those participants with poor discrimination at the apical end, the noise may have resulted in stimulation of SG cells over a considerable area, thus reducing the opportunity for these individuals to perceive speech sounds allocated to the same electrodes.

Looking back to results for experiment 1 part 1 (section 3.2.4), it is not easy to assess whether discrimination for apical electrodes had an effect on performance with the SG and Greenwood maps, as electrode discrimination was correlated with estimated insertion angle, which was correlated with performance with these maps for other reasons. A more extensive regression analysis would be needed to assess this, but this was not performed as there was insufficient data, due to the limited number of participants.

The mixed results with the RFR map suggest that further work in this area would be beneficial, and that frequency allocation may need to be determined on an individual basis in order for the optimal frequency map to be obtained.

4.4 Summary of Experiment 1 part 2

Performance was improved for some CI users when the frequency range of the map was reduced from 100-8500 Hz to 178-5612 Hz and logarithmic spacing of the frequency bands was introduced. These CI recipients had deep insertions and relatively poor electrode discrimination ability for apical electrodes. These results suggest that frequency allocation should be adjusted on an individual basis, and that a measure of electrode discrimination ability or insertion angle map help to optimise the fitting. As there was a better correlation between BKB scores and electrode discrimination than BKB scores and insertion angle, electrode discrimination rather than insertion angle is likely to be the more effective predictive measure.

4.4.1 Rationale for Experiment 2

The overall results of experiment 1 suggest that a change of frequency allocation away from the default setting will be helpful for a proportion of CI users, especially those with poor discrimination ability for apical electrodes. A map such as the RFR map with logarithmic frequency spacing and/or basal shift could bring about improvement. However, the RFR map resulted in poorer performance for some CI users in experiment 1. In view of this, there is a need to predict performance for individual CI recipients with different frequency maps and to find the optimal frequency allocation for individual recipients.

A second experiment was designed with the intention of testing a larger selection of frequency allocation settings with varying amounts of basal shift, to identify the optimum setting for individual CI recipients. It was anticipated that the best-performing map would be different for different participants. In order to avoid potential issues associated with deactivation of electrodes and difficulties with filters struggling with non-uniform frequency spacing, as in experiment 1 part 1, all available electrodes were activated (more detailed discussion of interaction between map parameters is given in section 2.4.3). In addition, the amount of truncation of the frequency range was limited, so that the number of fine structure channels would not differ greatly between the maps tested.

The results of experiment 1 part 2 showed a relationship between performance with the RFR map and electrode discrimination performance for apical electrodes. In order to build on this finding, a more detailed investigation of pitch perception for neighbouring electrodes was planned. Additionally, the findings from pitch perception tests in different parts of the cochlea would be incorporated into the speech perception analysis in an attempt to predict the optimum frequency allocation for individual CI users.

The results from experiment 1 suggested that participants had acclimatised to their clinical maps but this was not directly assessed. It was felt that an assessment of the perceived pitch and naturalness of the maps would help to shed more light on this issue. There would also be merit in assessing music perception for its own sake. Two music-related related assessments were planned for this purpose. Further details are given in section 5.2.5.

4.4.2 Research Questions for Experiment 2

1. Can speech perception for the group of participants be improved with one or more different frequency allocation settings, with logarithmic frequency spacing and basal shift relative to the clinical map?
2. Can speech perception for individual participants be improved with one or more different frequency allocation settings, with logarithmic frequency spacing and basal shift relative to the clinical map?
3. To what extent are the default frequency allocation and alternative allocations perceived as natural? Are they perceived as having normal pitch? Would music perception be adversely affected by a map with some basal shift and some loss of frequency range?
4. Can the optimum frequency allocation for an individual be predicted using pitch perception assessments for different electrodes?

4.4.3 Hypotheses

It was hypothesised that speech perception would be improved for some individual CI recipients with one or more of the alternative maps. Whether this would amount to a statistically significant improvement for the group of participants was uncertain. It was also hypothesised that performance on the pitch perception measure between electrodes would vary between participants and that it might be possible to use the pitch perception measure to predict performance on the speech perception measures.

It was hypothesised that the default map would be perceived as having close to normal pitch, as participants would have acclimatised to this map. It was anticipated that maps with basal shift relative to the default would be perceived as high pitched and less natural. The extent to which this would be the case would depend on the magnitude of the frequency shift.

Chapter 5: Experiment 2: Alternative Frequency Allocations for Individual CI Users

5.1 Pitch Perception along the Electrode Array

As it was hypothesised that the optimal frequency allocation will vary between participants, but that it might be possible to predict the optimum map from a pitch perception measure for individual electrodes, the pitch perception measure which was selected for and used in experiment 2 will be described and evaluated first. A more detailed and challenging assessment was required, as there were ceiling effects for the electrode discrimination test in experiment 1 and the number of trials was limited to eight per electrode pair. A new test, called the 'Pitch Contour Test' (PCT) was used. This test was developed for another PhD project (Roberts, A.M.H., not yet submitted). It has the advantage of testing both pitch direction changes (i.e. is a sound higher or lower in pitch than the previous one?) and pitch discrimination concurrently, thereby enabling pitch confusions to be distinguished from pitch reversals. It is also likely to be more challenging than the electrode discrimination task used in experiment 1 as identifying the direction of a change in pitch requires an additional step compared to simply identifying the fact that there has been a change.

5.1.1 Pitch Contour Test

The test is a 3I4AFC test, which uses the method of constant stimuli. There are 32 trials in each test. Each trial consists of a presentation of three pure tones, two of which have the same pitch (other stimulus types are available in the original version but only pure tones were tested in this experiment). The task for the CI user is to identify the order in which the sounds are presented, as there may be a low note followed by two high notes or a different arrangement. The four alternatives are represented on the GUI by black dots, as shown in Figure 45. The GUI also has a progress bar at the bottom to let participants know how far they are through the test.

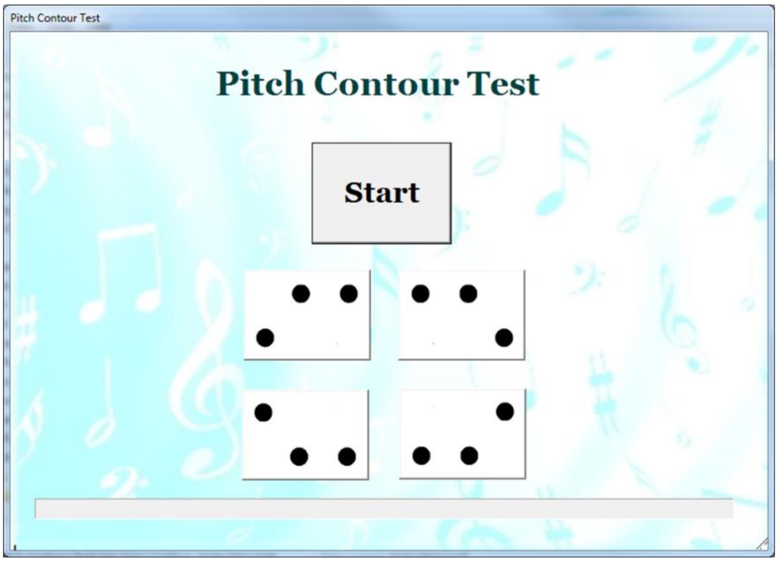


Figure 45 GUI for the PCT

The participant indicates their choice by pressing the appropriate button using the computer mouse.

For this experiment, the stimuli were pure tones with frequencies of 750 and 1150 Hz, frequencies which are above the range over which temporal cues are likely to be perceived from the temporal envelope (see section 2.1.2). A new map was made for each electrode pair and activated for the duration of the test only. The centre frequencies of the electrodes being tested were adjusted to the same frequencies as the test stimuli, to ensure that only the desired electrode was stimulated as far as possible. Comfort levels were balanced at 90% of Maximum Comfort Level (MCL). All other electrodes were deactivated. The strategy used was HD-CIS, to avoid additional temporal cues associated with the FS processing strategies. The rate of stimulation was the same as the rate in their default map if a participant used the FSP strategy or was adjusted to 1500 Hz if they used the FS4 or FS4-p strategy. The presentation level was set to 60 dB(A) with ± 2 dB of loudness roving, and the processor's microphone frequency response was taken into account when the stimuli were produced. A slightly reduced amount of loudness roving was used compared to that in experiment 1. This was thought to be sufficient as the same processor was used for all tests and the test was presented in Otocube, which gives very repeatable levels in different trials for frequencies within the range of 300 to 1500 Hz (within 0.5 dB) when the same spot is used for placement of the processor for these frequencies. Calibration was performed using a similar procedure to that in experiment 1 except that Otocube was used for the presentation and recording of the stimuli and only a single processor was tested.

The test also has a practice run, in which feedback is given, with 12 trials. Participants used their everyday map for the practice run. Pure tones with frequencies of 375 and 1500 Hz are compared for the first 8 trials in the practice run, followed by 750 and 1500 Hz for the remaining 4 trials. Participants repeat each trial until they obtain the correct answer.

For each trial, there is a 50% chance of getting the discrimination task correct as two of the four alternatives have either the first note or the third note as the odd one out. There is a 25% chance of getting the pitch contour (pitch direction task) correct, as only one of the alternatives has the correct note (first or third) moving in the correct direction from the previous one (either up or down). However, a score of 22/32 was required to be considered significantly above chance for both tasks. This is based on calculating the probability of a correct score being obtained by chance of less than 5%, from the binomial theory with a chance score of 50%. This was thought to be appropriate for the contour score as well as the discrimination score, as if a participant has discrimination ability, there will be a 50% chance that they will get the contour correct also. So the above chance score represents a statistically above chance measure for both tasks.

5.1.2 Methods

Participants performed the test for all their active electrodes (E) in pseudo-randomised order. An example map for the PCT for electrode pair E6E7 is shown in Figure 46. The figure shows the stimulation range from threshold level to comfort level for each electrode in charge units given by the manufacturer. In this case, the majority of electrodes are ‘greyed out’ as they are deactivated for the test. In the table within the figure, at the bottom, stimulation parameters for each electrode are given such as the pulse duration (also known as pulse width), centre frequency and rate of stimulation.

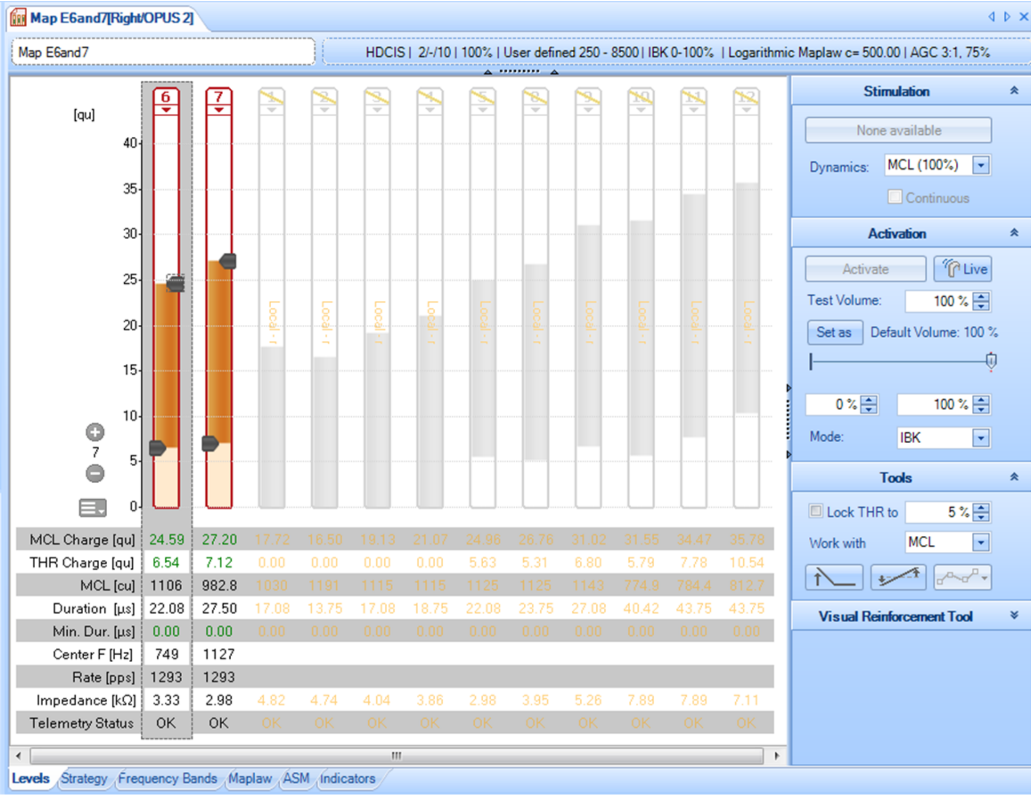


Figure 46 Example of a test map for the PCT, with only two active electrodes, HD-CIS strategy and adjusted frequency allocation.

5.1.3 Participants

Thirteen unilaterally-implanted, post-lingually deafened adult CI users were recruited for the experiment. All participants had been implanted for at least one year and had MED-EL CIs with either a standard (N=7) or Flex28 (N=6) electrode array. All participants had a full insertion of the electrode array, according to the surgeon's notes. All participants scored at least 80% correct on the BKB sentence test in quiet at their most recent annual review and were therefore considered to be good performers with their cochlear implants. All participants used the default frequency allocation. Participants P11, P12 and P13 had participated in experiment 1 (participants P3, P7 and P9 respectively). Further details relating to study participants at the time of testing are given in Table 10.

Table 10 Participants' details for experiment 2

Participant	Electrode array	Processing strategy	Age (years)	Duration of implant use (years)	Gender
P1	Standard	FS4-p	62	5	Male
P2	Flex28	FS4	59	1	Female
P3	Flex28	FS4	67	1	Female
P4	Flex28	FS4	66	1	Male
P5	Standard	FSP	69	10	Female
P6	Standard	FSP	76	15	Female
P7	Flex28	FS4	67	2	Male
P8	Flex28	FS4-p	28	2	Male
P9	Standard	FSP	49	8	Male
P10	Flex28	FS4	67	1	Female
P11	Standard	FS4	62	5	Female
P12	Standard	FSP	64	5	Male
P13	Standard	FS4	71	6	Female

Ethical approval for the study was obtained from the NHS National Research Ethics Service (reference 11/SC/0291), following a substantial amendment to the original ethics application. Those who participated in the experiment gave written informed consent.

5.1.4 Results

As the test had not been used for tuning purposes before and new stimuli had been produced for the test, the test itself was analysed in addition to the test results.

5.1.4.1 Ability to Perform the Procedure

All thirteen participants were able to complete the test, although three required help from the operator. In two cases, participants were unfamiliar with using a computer and required help with using the mouse. One participant found the graphical user interface confusing and gave verbal feedback to the operator. This participant was able to say, for example, 'High, low, low' or 'Low, high, high' but was unable to relate these statements to the visual representations of them on the screen.

5.1.4.2 Time Taken to Complete the Test

Time is required to prepare the maps used in the test, to loudness balance the comfort levels of the maps, to train the participant in the procedure, including performing a practise run and then to run the test.

Figure 47 shows the time taken for individual runs of the test, for participants who were able to perform the task without assistance. Loudness balancing and activation of the map was typically found to take two to four minutes per electrode pair. Approximately five minutes was required for explaining the test and performing the practice run for the majority of participants. For those requiring assistance, the time taken to complete a run ranged from three to seven minutes; the time between runs was also longer (two to five minutes). For most individuals, a realistic testing time is 30 minutes for five electrode pairs.

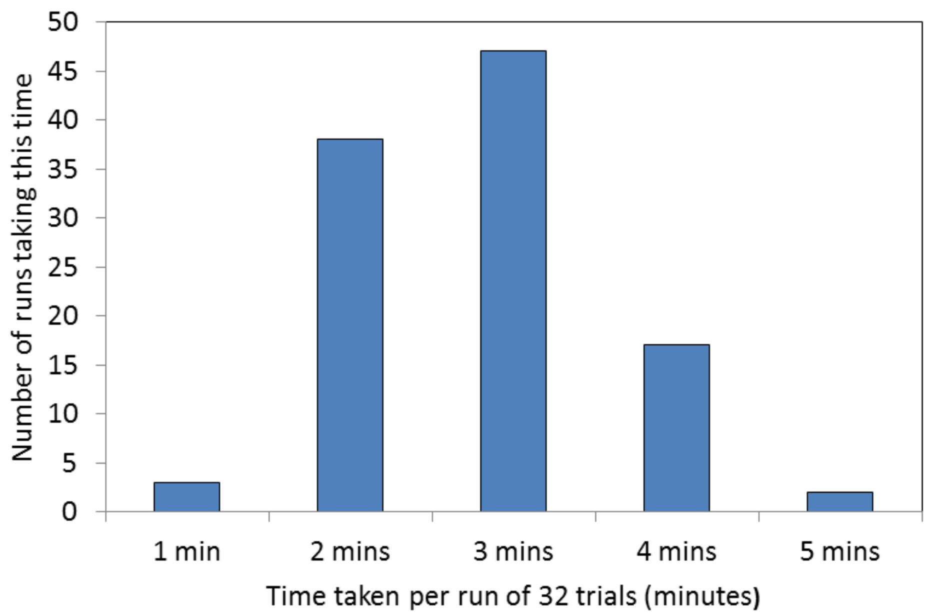


Figure 47 Time taken to complete individual runs of the PCT

5.1.4.3 Performance on the Test

Performance was scored separately for pitch contour and pitch discrimination. A summary of results for all participants and all electrode pairs is shown in Figure 48.

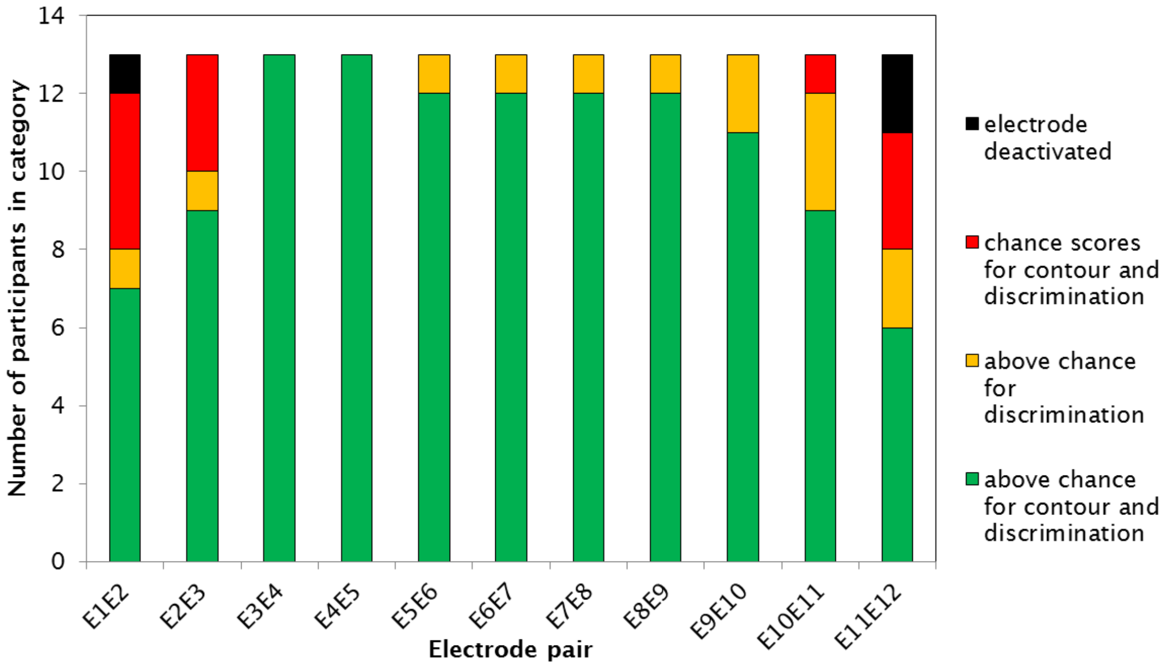
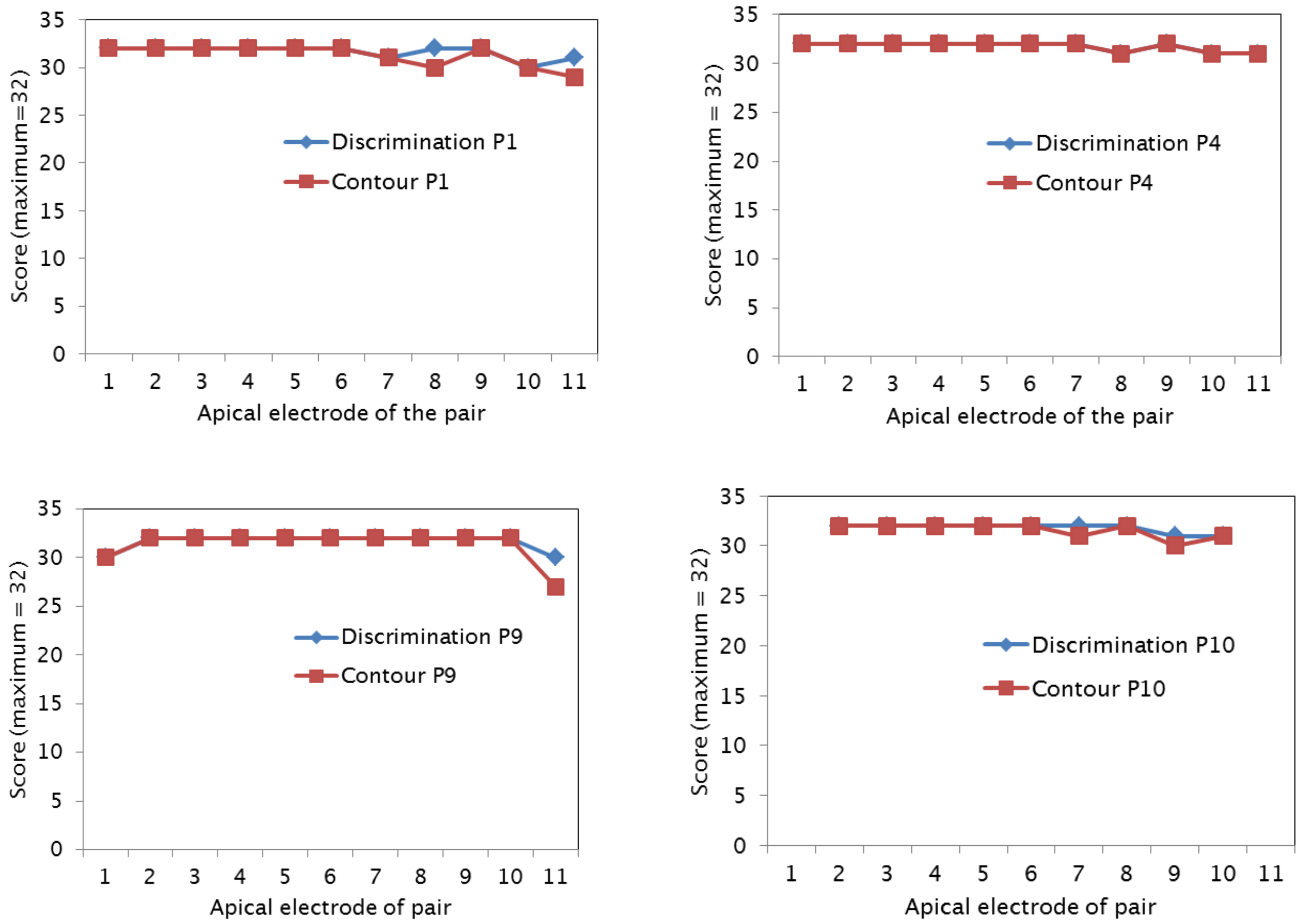
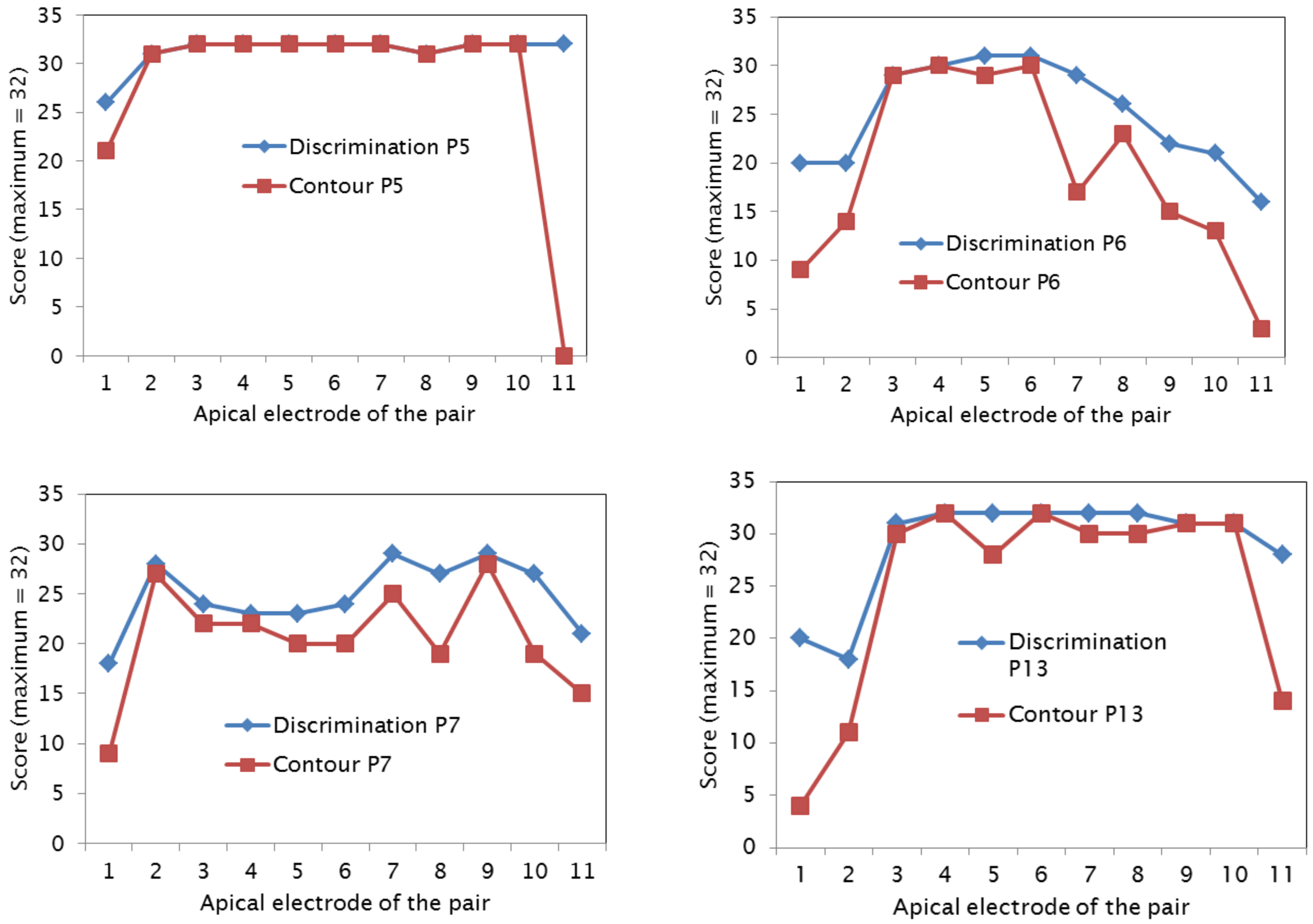


Figure 48 Summary of PCT results for all participants for all electrode pairs

It was found that four participants were able to score above chance (score ≥ 22/32) for all electrode pairs for both contour and discrimination (P1, P4, P9 and P10). Four participants had some difficulty at both ends of the array (P5, P6, P7 and P13) whilst two participants had difficulties at the apical end only (P11 and P12) and two participants had difficulties at the basal end of the array only (P2 and P3). One participant had difficulty with the contour for one electrode pair in the middle of the array (P8). PCT scores are shown in Figure 49.


Discrimination P1
Contour P1
Score (maximum=32)
Apical electrode of the pair
Discrimination P4
Contour P4
Score (maximum = 32)
Apical electrode of the pair
Discrimination P9
Contour P9
Score (maximum = 32)
Apical electrode of pair
Discrimination P10
Contour P10
Score (maximum = 32)
Apical electrode of pair

Experiment 2



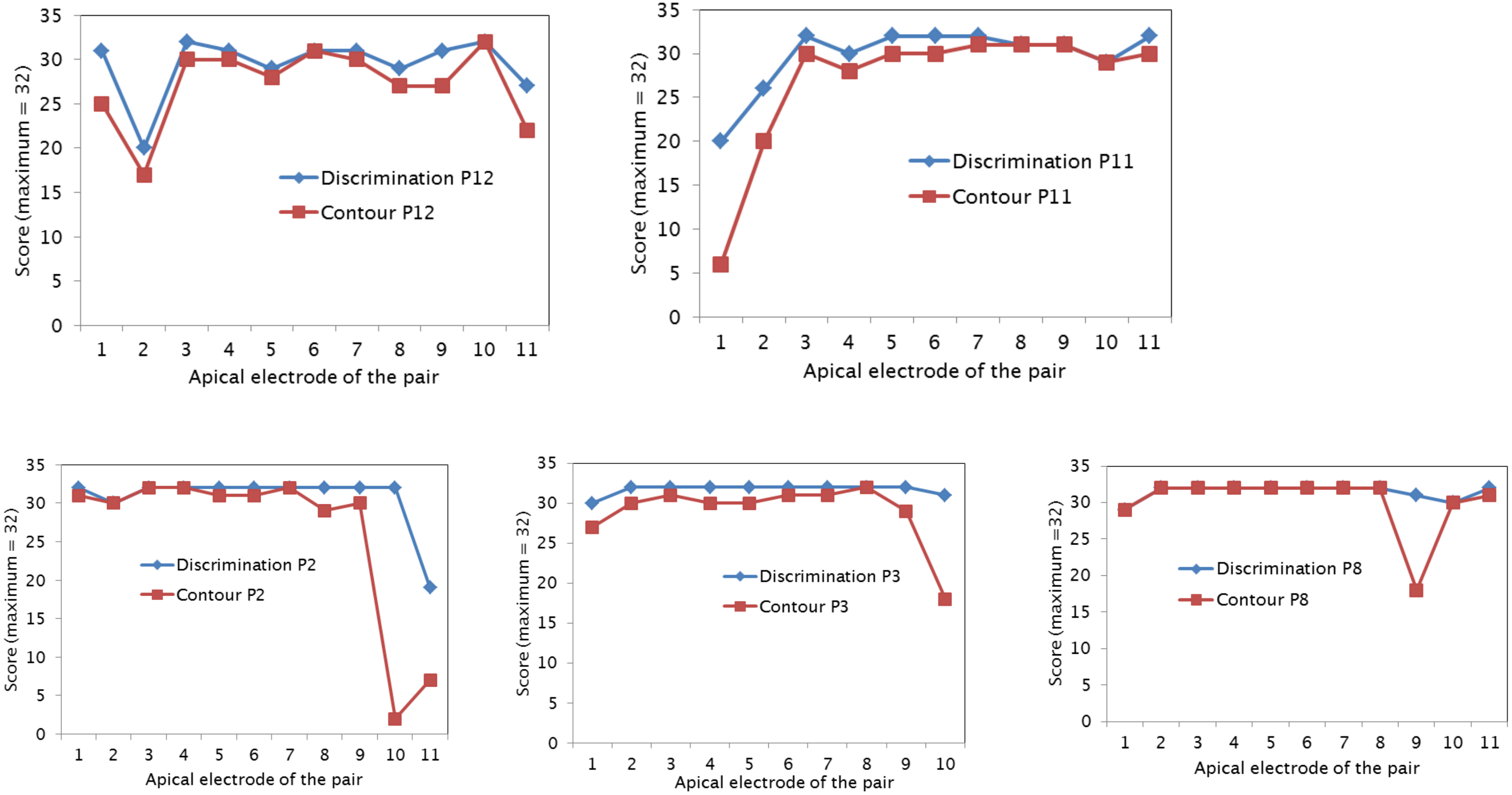


Figure 49 PCT scores for individual participants for individual electrode pairs

5.1.4.4 Statistical Analysis

Friedman's test was used to compare variables which were not normally distributed; Wilcoxon's signed ranks test was used to compare two variables which were not normally distributed.

Discrimination scores for all electrodes for the group are shown in Figure 50.

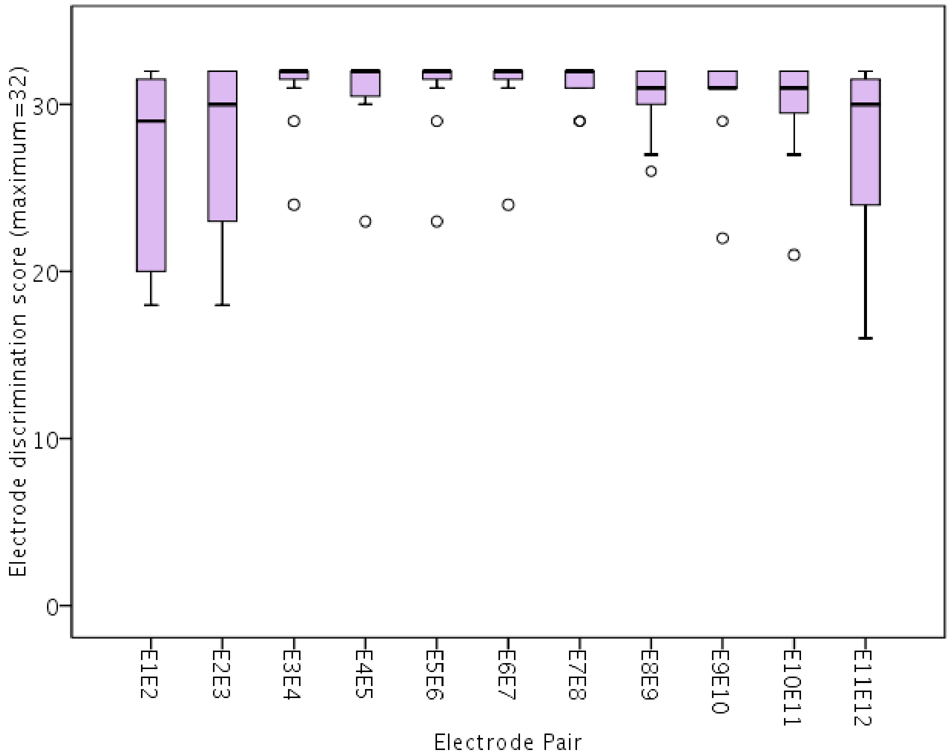


Figure 50 Discrimination scores for the PCT for 11 participants with all electrodes active in their maps. The median value is shown as a heavy line. The box represents the range between the 25th and 75th centiles. Whiskers represent the range of data, unless this extends beyond 1.5*the inter-quartile range from the box, in which case data points are indicated by small circles as outliers.

Analysis was performed for the eleven participants who had all electrodes active in their map. Scores were not normally distributed for any of the electrode pairs for discrimination or contour scores. Friedman's test was used to analyse discrimination scores. A significant effect of electrode pair was found [$\chi^2(10)=34.2$, $p<0.001$]. Individual electrode pairs were compared using Wilcoxon signed ranks test. All electrode pairs were compared with electrode pair E6E7, as these electrodes are in the middle of the electrode array. It was found that electrode pairs E1E2 and also E11E12 gave poorer results on the discrimination part of the test than electrodes E6E7 [$Z=-2.53$, $p=0.011$, $r=0.57$ (a large effect) for electrodes 1 and 2; *Z*=-2.53, *p*=0.012, *r*=0.57 (a large effect) for electrodes 11 and 12]. Bonferroni corrections were not applied, as this would have contradicted the result of Friedman's test.

Contour scores for the group for all electrodes are shown in Figure 51.

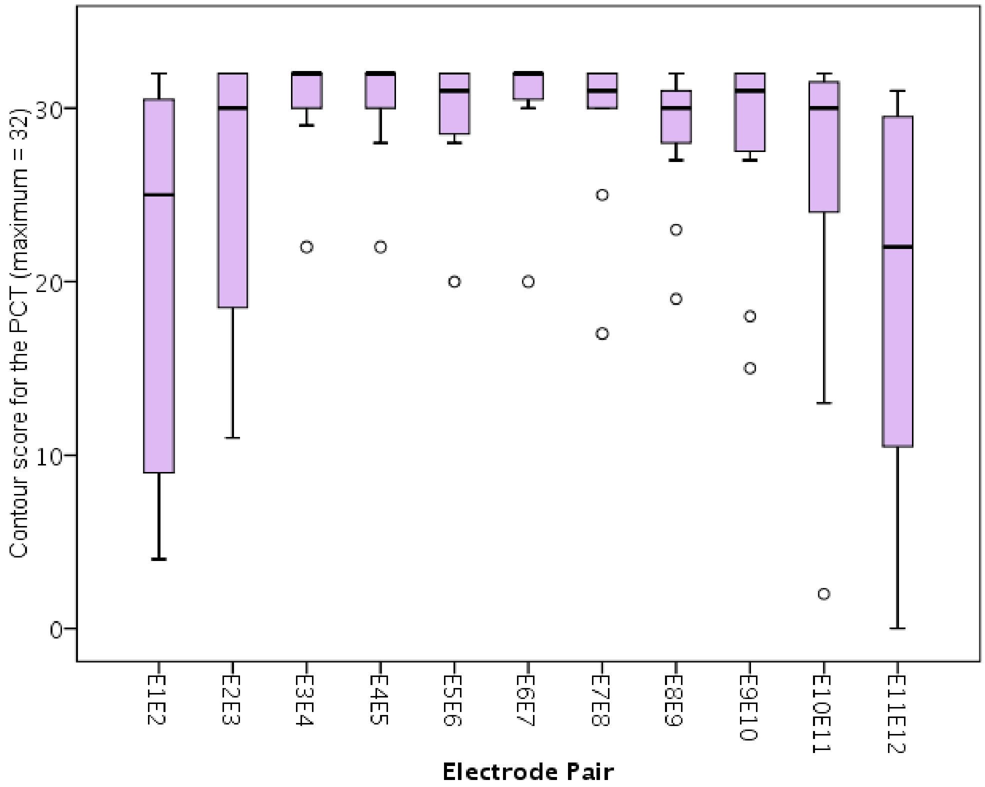


Figure 51 Contour scores for the PCT for participants with all electrodes active in their maps. The median value is shown as a heavy line. The box represents the range between the 25th and 75th centiles. Whiskers represent the range of data, unless this extends beyond 1.5*the inter-quartile range from the box, in which case data points are indicated by small circles as outliers.

Friedman's test was also used to analyse contour scores. A significant effect of electrode pair was found [$\chi^2(10)=46.5$, $p<0.001$]. Individual electrode pairs were compared using Wilcoxon signed ranks test (2-tailed). It was found that electrode pairs E1E2, E2E3, E8E9, E10E11 and E11E12 all offered poorer performance than electrode pair E6E7. However, no Bonferroni corrections were applied, to be consistent with the discrimination test results [*Z*=-2.668, *p*=0.008, *r*=-0.52 for E1E2; *Z* =-1.97, *p*=0.049, *r*=-0.39 for E2E3; *Z*=-2.23, *p*=0.026, *r*=-0.44 for E8E9; *Z*=-2.671, *p*=0.008, *r*=-0.52 for E10E11 and *Z*=-2.807, *p*=0.005, *r*=-0.55 for E11E12]. So there were large effects for electrode pairs E1E2, E10E11 and E11E12; there were medium effects for E2E3 and E8E9.

5.1.5 Discussion

5.1.5.1 Evaluation of the Test

The majority of participants were able to perform the test without difficulty. In two cases it was more difficult as participants were unfamiliar with using a computer. In one further case, the participant found the GUI confusing. In view of this, it may be worthwhile to have an option for the buttons to display 'high, high, low' or 'low, low high' etc. rather than the dots which are currently used.

The test took quite a long time to perform for all electrode pairs (approximately 1 hour). This means that in general clinical practice, it would not be convenient to test all electrode pairs, certainly not in a single session.

The fact that the test picked up differences in performance across the electrode array suggests that calibration/loudness roving/loudness balancing was successful. The fact that it was possible to see differences between contour and discrimination scores allowed pitch reversals to be distinguished from pitch confusions. This was facilitated not just by the test method but also by the considerably larger number of trials used in this experiment compared to the electrode discrimination task used in experiment 1.

5.1.5.2 Test Outcomes

Whilst some participants scored at above chance levels for all electrode pairs for contour and discrimination, others did not. In particular, discrimination was poorer for the group for electrode pairs E1E2 and E11E12 (at the ends of the array) and contour was poorer for the group for five electrode pairs, of which two were at the apical end of the array and two were at the basal end of the array, when compared to E6E7 in the middle of the array. This is interesting for two reasons. Firstly, it is consistent with the idea that there are fewer SG cells available for stimulation at either end of the array. Whilst poor pitch perception at the apical end was anticipated for a proportion of CI users (see section 4.4.3), poor pitch perception at the basal end had not been anticipated to the same extent. Electrode discrimination at the basal end of the array this was more difficult to assess in experiment 1 as not all participants had a full insertion of the array. The second reason why the discrimination results are interesting is that discrimination scores were better for this group of participants for electrode pair E2E3 than the group who participated in experiment 1.

Another interesting finding is the fact that pitch contour was poorer than discrimination for three electrode pairs. This is consistent with the fact that identifying the pitch contour takes an additional step compared to discriminating the odd note out correctly. In addition, examples of both pitch confusion and pitch reversals were found. For example, P2 has a pitch reversal for electrode pair E10E11, where discrimination is good but contour is very poor, and a pitch confusion for E11E12 where both contour and discrimination scores are at chance level.

For the middle electrodes, most participants achieved ceiling scores. This is not an ideal result, as it is not possible to see whether there were differences in pitch perception for this part of the electrode array for most participants. A possible way to reduce ceiling effects would be to test frequencies between the centre frequencies of adjacent electrodes.It was hypothesised that poor pitch perception at either end of the array may affect speech perception, especially if adjustment of the frequency allocation resulted in important speech frequencies being moved to an area of the cochlea with poor pitch perception. As a result of this, contour scores for the two electrode pairs at either end of the array were entered into the analysis of BKB sentence scores for the main part of experiment 2.

5.2 Design of Experiment 2: Alternative Frequency Allocations

Experiment 2 was an acute study, which assessed performance with different frequency allocations: take-home experience was not incorporated into the design of the experiment, as the intention was to test a larger number of frequency allocation settings than had been attempted in experiment 1. It was not therefore practical to incorporate take-home experience for each map. Immediate improvement in performance was seen for sentence perception with the RFR map, so take-home experience was not considered necessary, so long as the frequency shift was limited to a tolerable amount.

5.2.1 Adjustment of CI frequency allocations

Ten different maps were created for each participant in the experiment, with varying amounts of frequency shift relative to the default map. The maps differed in their frequency allocation settings but no other parameters were altered. One of the study maps was each participant's own clinical map, which used the default frequency allocation in every case. This has a frequency range of 100 to 8500 Hz and allocates a larger portion of the frequency range to the apical electrodes than the basal electrodes. The alternative maps all had uniform (logarithmic) frequency spacing but different frequency ranges. The lower frequency boundaries were 225 (L0), 179 (L1) and 142 (L2) Hz and the upper frequency boundaries were 5353 (U2), 6746 (U1) and 8500 (U0) Hz, or as close to this as the processor's filter settings allowed. This meant that the frequency shift on each electrode for the centre frequency for all maps was always less than one octave, when compared to the default map, and for the basal half of the electrode array did not exceed 0.67 octaves. Studies by Fu *et al.* (1998), Fu and Shannon (1999c), Başkent and Shannon (2003), Zhou *et al.* (2010), have found that normal-hearing listeners are tolerant of frequency shifts of up to approximately 0.7 octaves when listening to CI simulations.

The map L0U0 had the same frequency allocation as the default map for basal electrodes, but had a different frequency allocation function shape for the apical electrodes and some associated apical shift for those electrodes, as shown in Figure 52(a). It was anticipated that this map would have the lowest pitch percept. The amount of basal shift was measured relative to this map. The numbers 1 and 2 for the lower and upper frequency boundaries represent shifts of one third (400 cents) and two thirds (800 cents) of an octave respectively, so the map L2U2 has a basal shift of two thirds of an octave across the whole electrode array, when compared to map L0U0. Map L0U2 has no frequency shift at the apical end but a frequency shift of two thirds of an octave at the basal end. Figure 52(b) shows the details of a selection of the alternative maps for all electrodes whilst Figure 52(c) shows details of the default and U1 maps at the apical end of the array.

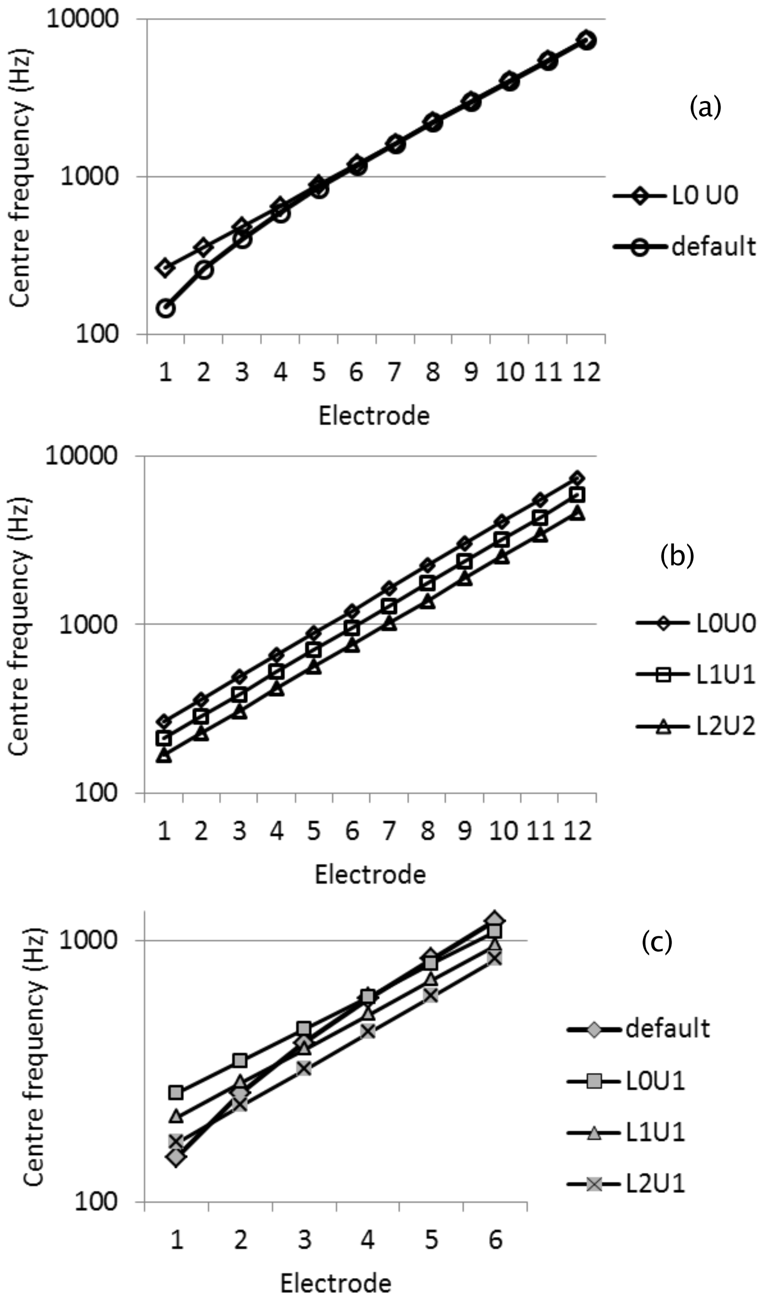


Figure 52   Frequency allocations for experiment 2 (a) centre frequencies of the L0U0 and default maps (b) maps L0U0, L1U1 and L2U2 (c) centre frequencies for electrodes 1 to 6 for U1 maps and the default

For participants with the FSP strategy, some of the alternative maps had a different number of fine structure channels. The number of fine structure channels increased from one to two for P5 and from three to four for P12 for the four most basal maps; the number of fine structure channels increased from one to two for the L2 maps for P9 but decreased to zero for maps L0U0 and L0U1; an increase in the number of fine structure channels might increase the temporal cues available to these participants for these maps. No electrodes were deactivated in order to fit any of the experimental maps, so for each participant the number of electrodes activated in each map was the same as for their normal clinical (default) map. There were no changes to the rate of stimulation or any other parameter between maps (see section 2.4.3 for further information about covariance of CI stimulation parameters).

5.2.2 Assessments

As in experiment 1, speech perception and music perception were incorporated into the design of the experiment. However, there were some differences in the methodology and these are detailed below. One difference which was common to all the assessments was that they were presented via a sound-treated box containing a loudspeaker, Otocube. A test processor (Opus 2), connected to a long coil cable, was used throughout.

5.2.3 BKB Sentence Test

The BKB sentence test was used to assess speech perception. This test proved to be sensitive to changes of frequency allocation in experiment 1 and it was anticipated that the same would apply for experiment 2. New extended lists of sentences were used for experiment 2, which were presented via the AstonSoundLite program (use of the standard lists would have required all the available sentences to be presented, which could impact on normal clinical assessments). The extended sentences use the same vocabulary as the original sentences, have the same number of keywords per sentence and are spoken by the same speaker but there are a greater number of sentences available. The sentences were organised into lists. For the determination of the signal to noise ratio (SNR) at which each participant was to be tested with the different maps, lists of 16 sentences, each containing three or four keywords were compiled, with no repetition of the same keyword within a list. Sentences were presented in speech-shaped noise at 65 dB(A) and the SNR for which the participant scored between 60 to 70% correct with their everyday clinical map was found. Speech-shaped noise with this SNR was used for the main test. For the measurement of performance with each frequency allocation, lists of 32 sentences each containing 100 keywords were used and again there was no repetition of a keyword within a list. The order of testing of the maps was pseudo-randomised; five maps were tested in the first session and the remaining five in the second session for each participant.

5.2.4 Vowel Recognition Test

The vowel recognition test was unchanged from experiment 1 (see section 3.1.8), except for the use of Otocube. This test proved to be sensitive to changes of frequency allocation in experiment 1.

Participants performed the task with each study map. Five maps were tested in each of the two sessions in pseudo-randomised order. It was anticipated that vowel perception would be relatively unaffected by spectral shift in this experiment, as the amount of basal shift was limited. If there proved to be an effect for the maps with the largest amount of shift, it was anticipated that vowels with relatively low formant frequencies would be mistaken for vowels with relatively higher formant frequencies. It was anticipated that performance would only be affected by poor pitch perception at the ends of the electrode array if formant frequencies were assigned to those electrodes.

It has been found in previous studies that vowel perception is adversely affected by poor spectral resolution in CI users (see for example Harnsberger *et al.* (2001)). It was anticipated that performance on this test might improve if the new maps resulted in formant frequencies being assigned to areas of better pitch perception.

As a larger number of maps were tested than in experiment 1, vowel identification error patterns were analysed in addition to overall test scores. The vowel space for this test is shown in Figure 53. Based on the difference in formant frequencies for F1 and F2, it is more likely that ‘hard’ will be confused with ‘heard’ than vowels with more different F1 and F2 such as ‘heed’ or ‘hid’.

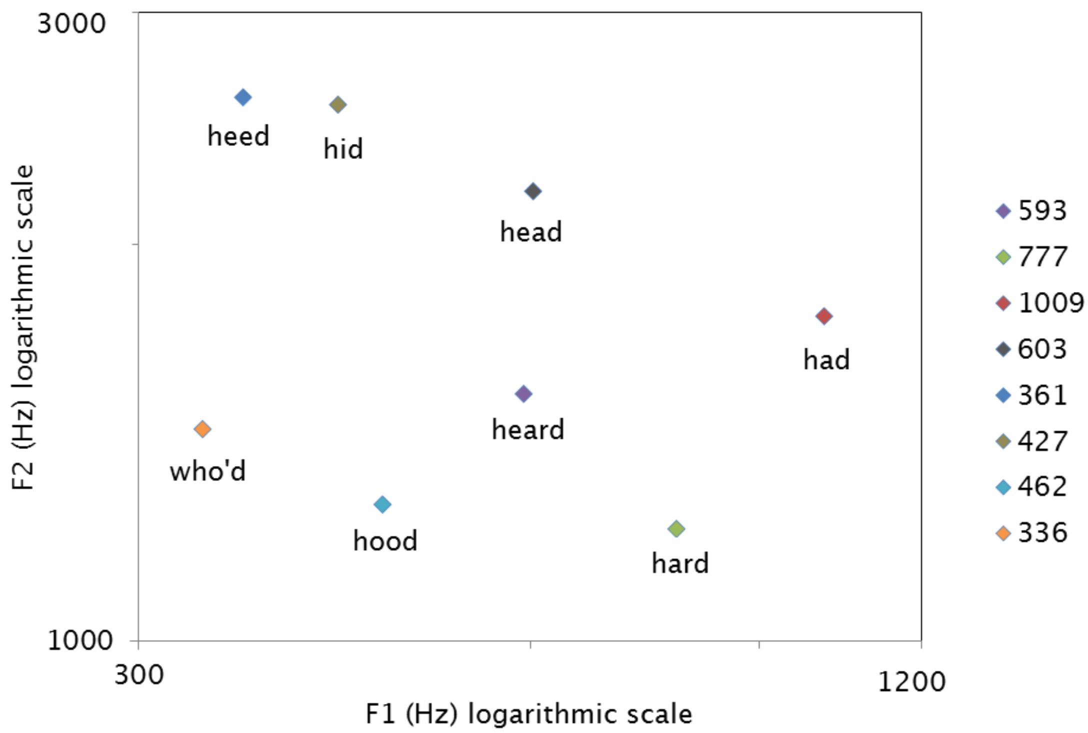


Figure 53 Vowel space for the tokens used in the vowel identification test. The legend shows F1 frequencies (Hz).

The spread of formant frequencies over the different electrodes was considered for a 12 channel map, in order to see if there might be a potential advantage or disadvantage of using a map with logarithmic spacing for this test.

Table 11 shows the allocation of formant frequencies for two of the maps.

Table 11 Formant frequencies for tokens used in the vowel test and the electrodes to which the tokens are assigned

word	F1 (Hz)	F2 (Hz)	F1 electrode with default map	F2 electrode with default map	F1 electrode with L1U1 map	F2 electrode with L1U1 map
heed	350	2628	3	9	3	9
who'd	365	1701	3	7	3	8
hid	427	2540	3	8	3	9
hood	461	1276	3	6	4	7
heard	594	1543	4	7	4	8
head	598	2179	4	8	4	9
hard	777	1217	5	6	5	7
had	1005	1769	6	7	6	8

It can be seen that F1 for half of the vowel tokens is assigned to E3 for the default map. The situation is only slightly different for the map with logarithmic frequency spacing, where the F1 frequencies for three tokens are assigned to E3.

5.2.5 Music Perception Assessment

The piano notes discrimination task only tested a small aspect of music perception and even this did not prove to be very informative in experiment 1. In order to assess music perception in a more functional way, subjective sound quality was assessed in addition to the perceived pitch of the map for each of the different frequency allocations. Subjective sound quality has been used to assess music perception in previous studies, see for example Moore and Tan (2003) and has been shown to be sensitive to frequency range.

It was anticipated that music sound quality might be improved if pitch perception was improved, but would be reduced if either basal shift was sufficient to be noticeable or if the frequency range was reduced to the point where this impacted on the music's sound quality.

5.2.5.1 Sound Quality Ratings

Participants listened to verse 1 of a song by Sir Cliff Richard, 'We don't talk anymore' with each study map, presented in a pseudo-randomised order.

Frequency analysis for the main vocals for the word ‘one’ in the penultimate line of verse one is shown in Figure 54. It can be seen that the vowel /^/ from ‘one’ has highest energy for frequency bands centred around 630, 1000, 1250 and 2500 Hz.

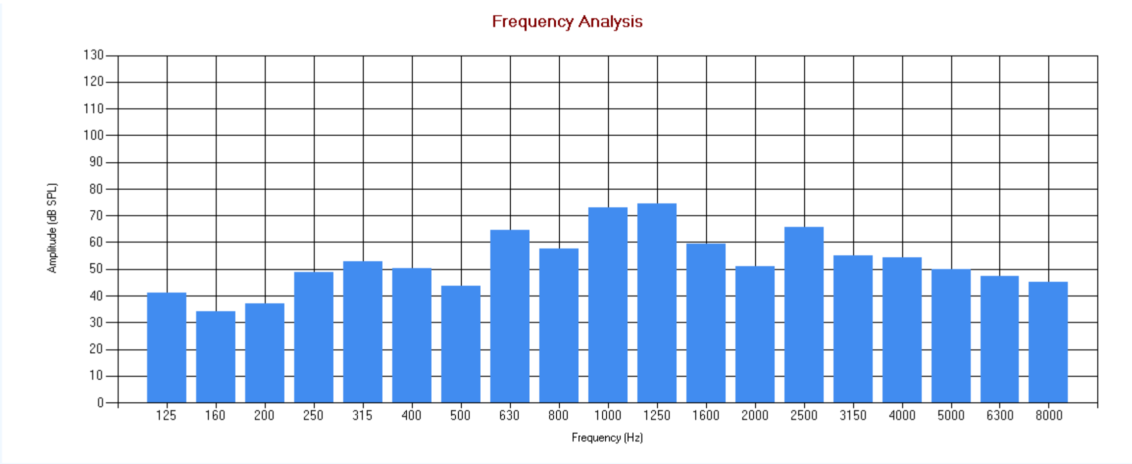


Figure 54 Frequency analysis for the utterance ‘one’ from the penultimate line of verse one (main vocals only)

This verse of the song has fundamental frequencies from 175 to 349 Hz. For the L0 maps, the fundamental frequency would therefore be attenuated for the lower notes. Temporal pitch cues may have been available for some notes, but were unlikely to be available for the highest ones, as they had F0 above 300 Hz (Zeng, 2002). For the U2 maps and to a lesser extent the U1 maps, high frequency sounds, such as those >5 kHz, would have been attenuated.

Participants were asked if they were familiar with the song and were able to answer ‘Yes’, ‘No’ or ‘Not sure’. Presentation of the song was via the mixer app from the Interactive Music Awareness Programme (IMAP) (van Besouw *et al.*, 2013), which plays a video of the song, along with subtitled lyrics. The volume level was set to 60 dB(A). Participants listened to a verse of the song, both the vocals and the backing tracks, and were able to watch the video too. They then rated the naturalness of the song on a visual analogue scale, which was labelled as ‘Unnatural’ on the left side of the paper and ‘Natural’ on the right side of the paper. Participants were then asked, ‘Do you think that the pitch is correct?’ and indicated if the pitch was correct using a visual analogue scale labelled ‘Very low’ on the left of the page, ‘Correct pitch’ in the middle, and ‘Very high’ on the right of the page. The backing tracks were then switched off, using the IMAP software, so that only the main vocals were heard. After listening to verse one again, participants rated the clarity of the lyrics on a visual analogue scale extending from ‘Unclear’ on the left of the page to ‘Clear’ on the right of the page, as shown in Appendix 4. The visual analogue scale was used as this allowed fine judgements to be made, without the need for negative numbers to be included in the scale.

5.2.5.2 Adjustment of Musical Pitch

The mixer app in the IMAP has a slider for the adjustment of pitch, as shown in Figure 55, which allows the pitch of the song to be adjusted in real time from one octave below the normal pitch to one octave above it, using a frequency-domain pitch shifter. The pitch slider was demonstrated to participants by the tester but no information was given relating to the direction or amount to which it should be adjusted. Participants were asked to adjust the pitch of the song, to correct it, whilst listening to the same verse again, with each map. They were free to continue with just the vocals or could add in the backing tracks if they wished to do so, by pressing the icon corresponding to each instrument on the screen. An additional field was included in the IMAP software for this experiment, which shows the change of pitch in cents (from the original). This number was recorded for the pitch adjustment for each map.

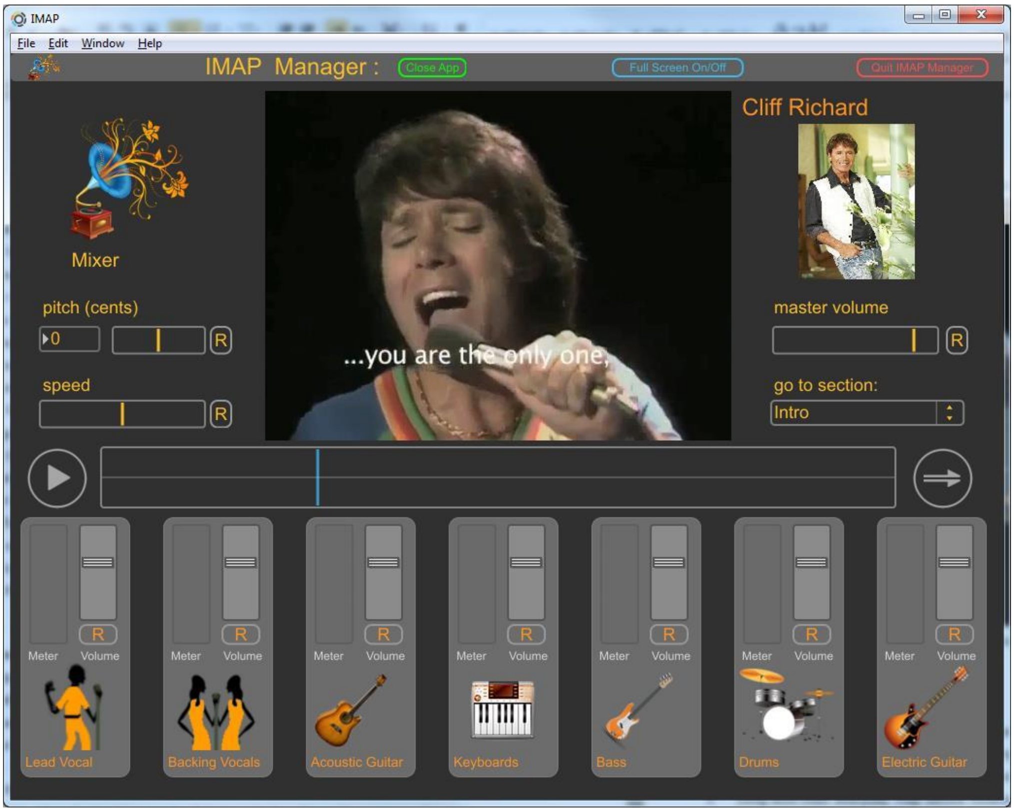


Figure 55 GUI for the song presented for the music assessment, showing the pitch slider

5.2.5.3 Participants

One participant dropped out of this part of the experiment (P7) because he was unfamiliar with using a computer, had some other difficulties, and found the adjustment of the pitch slider, described below, too difficult to manage using a computer mouse. Another participant, P6, found that the singer's voice sounded 'hoarse' through her CI and the rough sound quality meant that she was unable to perceive the pitch of the singer's voice. She also found this part of the experiment too difficult and dropped out. Results were obtained for the remaining eleven participants.

Details of participants' prior engagement with music were drawn from their clinical notes. It was found that music was a serious hobby for two participants: P1 learnt the piano until the age of nineteen, whilst P8 enjoyed writing songs. P9, P11 and P13 had had a limited amount of musical training at school; no data was available for P4 in relation to previous music training but music was not highlighted as an important issue in his assessment notes. The remaining participants all reported that they had enjoyed listening to music, before losing their hearing, but had not received formal music training.

5.3 Results

5.3.1 Statistical Analysis

Repeated-measures ANOVA was used to investigate the effect of frequency allocation on test results, where data were normally distributed. The Greenhouse-Geisser correction was applied if the condition of sphericity was violated. Pairwise comparisons were conducted post-hoc and within-subjects contrasts were used to investigate interaction effects. Effect sizes are reported as '*r*' and were calculated from the *F*-ratio for within-subjects contrasts. Where sufficient data was available, PCT scores for both apical and basal electrodes were incorporated into the analysis.

Friedman's test was used to compare a number of variables which were not normally distributed; Wilcoxon's signed ranks test was used to compare two variables which were not normally distributed.

As ten measurements were made for each participant for this experiment and thirteen people participated in the speech perception tasks, the experiment had greater power than experiment 1 (see section 3.2.1). In fact a power calculation for a repeated-measures design with 13 participants has power of 0.78 for within-subject comparisons, which is close to the desired amount of 0.8. However, as more conditions were tested and therefore more paired comparisons were made, there was a greater need for control of Type II errors than there had been in experiment 1. If all the paired comparisons which were possible were performed this would amount to a great number of comparisons (e.g. to compare each map with each other map would mean 45 comparisons). The Sidak corrections applied in experiment 1 are not appropriate in cases where the assumption of sphericity is violated for ANOVA (Field, 2005), so Bonferroni corrections were applied but the number of comparisons made was limited. The L0U0 map was compared with the other maps in most cases. Further details are given in the text.

Data is presented in the form of bar graphs, scatter plots and boxplots. Where ten maps were compared and data were normally distributed, bar graphs were used, as these were easier to visualise than a large number of box plots. For the bar graphs, the bar represents the mean and error bars represent one standard deviation. For the boxplots, the median value is shown as a heavy line. The box represents the range between the 25th and 75th centiles. Whiskers represent the range of data, unless this extends beyond 1.5*the inter-quartile range from the box, in which case data points are indicated by small circles as outliers.

5.3.2 BKB Sentence Test

Results for the BKB sentence test were found to be normally distributed for all ten maps. These are shown in Figure 56.

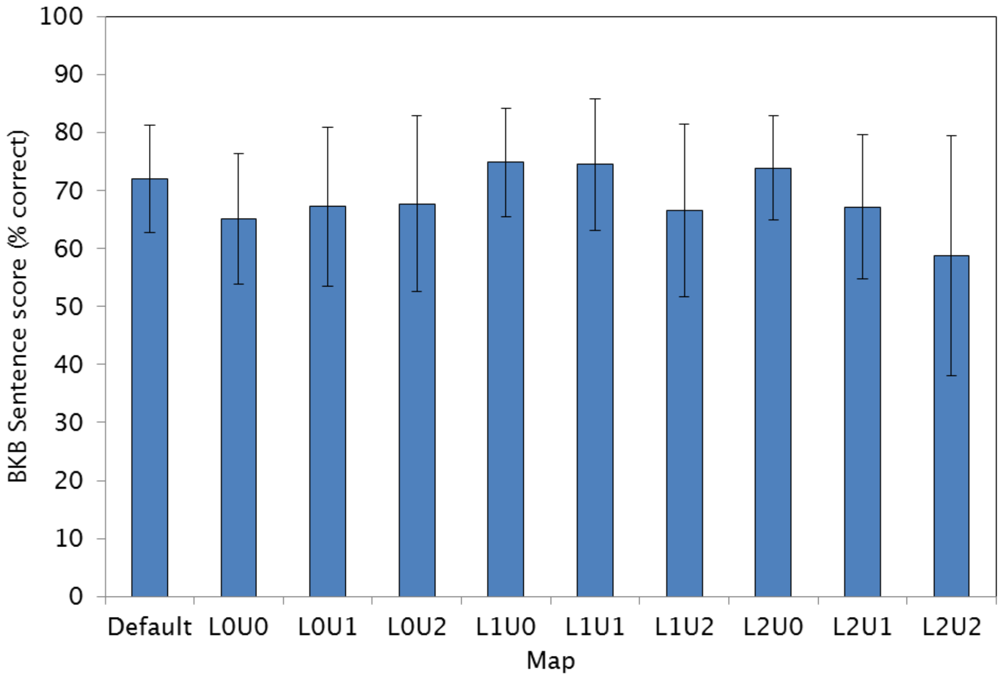


Figure 56 BKB sentence scores with different maps in experiment 2. Boxes show the mean for each condition and error bars show one standard deviation.

The influence of PCT score for apical electrodes and basal electrodes was investigated within the analysis of BKB scores. Repeated-measures ANOVA was performed with between-subjects measures of PCT score for apical electrodes (either above chance or not for E1E2 and E2E3) and similarly for PCT scores for basal electrodes (either above chance or not for E10E11 and E11E12). Mauchly's test of sphericity gave a significant result for this data: [$\chi^2(44)=93.1$, $p<0.001$]. The Greenhouse-Geisser correction was applied in view of this. ANOVA showed a significant main effect of map on BKB sentence test score [$F(4.24,38.2)=7.14$, $p<0.001$]. There was also a significant interaction between BKB score and PCT score for basal electrodes [$F(4.24,38.2)=2.95$, $p=0.03$] but no significant interaction between BKB score and PCT score for apical electrodes [$F(4.24,38.2)=1.31$, $p>0.05$]. There was no independent effect of PCT score for basal electrodes [$F(1,9)=0.865$, $p>0.05$] or apical electrodes [$F(1,9)=0.289$, $p>0.05$].

Pairwise comparisons were conducted, in which Bonferroni corrections for nine comparisons were applied. BKB sentence scores for the whole group were compared for each map with those for the L0U0 map, which was the most apical logarithmic map. Results indicated that the L1U0 and L1U1 maps offered better performance on the test than the L0U0 map [$p=0.018$, $r=0.82$ for L1U0 and $p=0.009$, $r=0.84$ for L1U1, both large effects]. Performance with the L0U0 map was not significantly different to performance with any of the other maps, including the default map [$p>0.05$].

Within-subjects contrasts investigating the interaction between PCT score for basal electrodes and BKB sentence score, suggested an interaction between BKB sentence score and basal PCT score for the L1U1 map, when compared to the L0U0 map [$p=0.008$, $r=0.75$, a large effect] and to a lesser extent for the L0U1 map [$p=0.033$, $r=0.64$], L1U2 map [$p=0.018$, $r=0.69$] and L2U2 maps [$p=0.042$, $r=0.62$], all large effects. However, these contrasts were made without Bonferroni corrections, which would have contradicted the result of the ANOVA. The interaction between BKB scores and PCT scores for basal electrodes suggests that participants with above chance scores for basal electrodes on the PCT performed better with the L1U1 map than participants with chance or below chance scores. Results for participants according to PCT scores for basal electrodes are shown in

Figure 57 for maps, L0U0, L1U1, L1U2, L0U1 and L2U2.

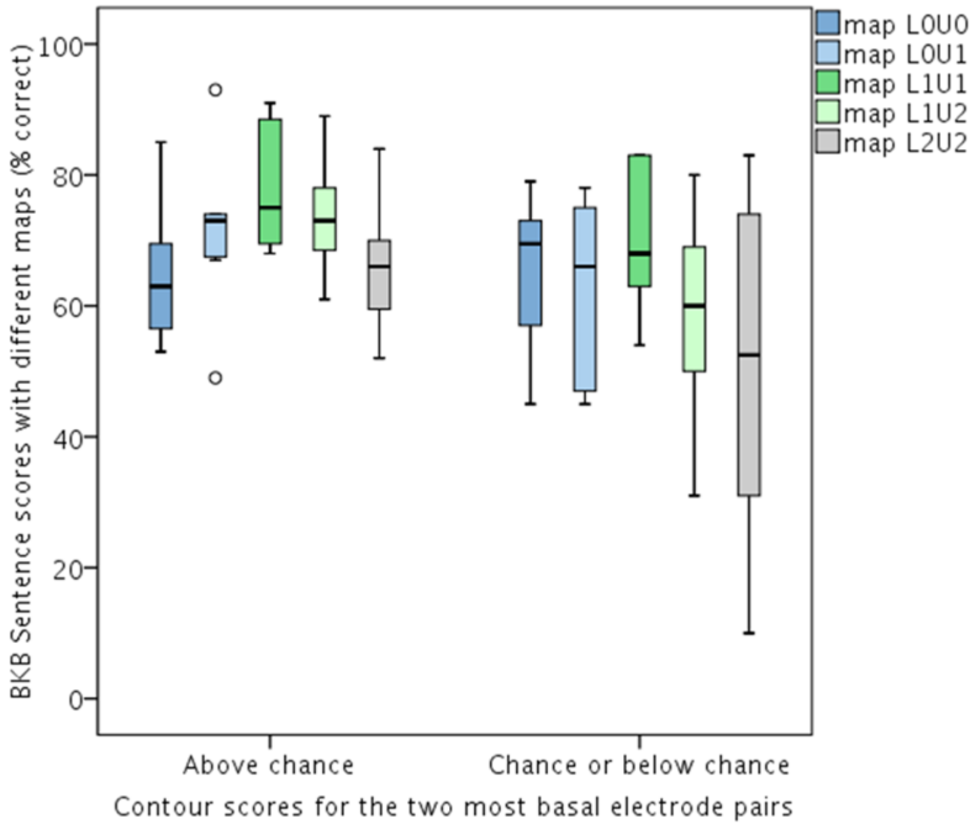


Figure 57 Interaction between contour score for basal electrodes and BKB sentence scores with different maps.

To consider the effects of the upper and lower boundaries separately, new variables were calculated. The scores for maps with a lower frequency boundary of L0 (L0U0, L0U1 and L0U2) were averaged to calculate the variable L0 and similarly for variables L1, L2, U0, U1 and U2. The new variables were all found to be normally distributed. Results with the different lower frequency boundaries are shown in Figure 58 and with the different upper frequency boundaries in Figure 59. As an interaction between BKB score and PCT score for basal electrodes had been found, PCT score for basal electrodes was taken forward into the analysis of the averaged variables.

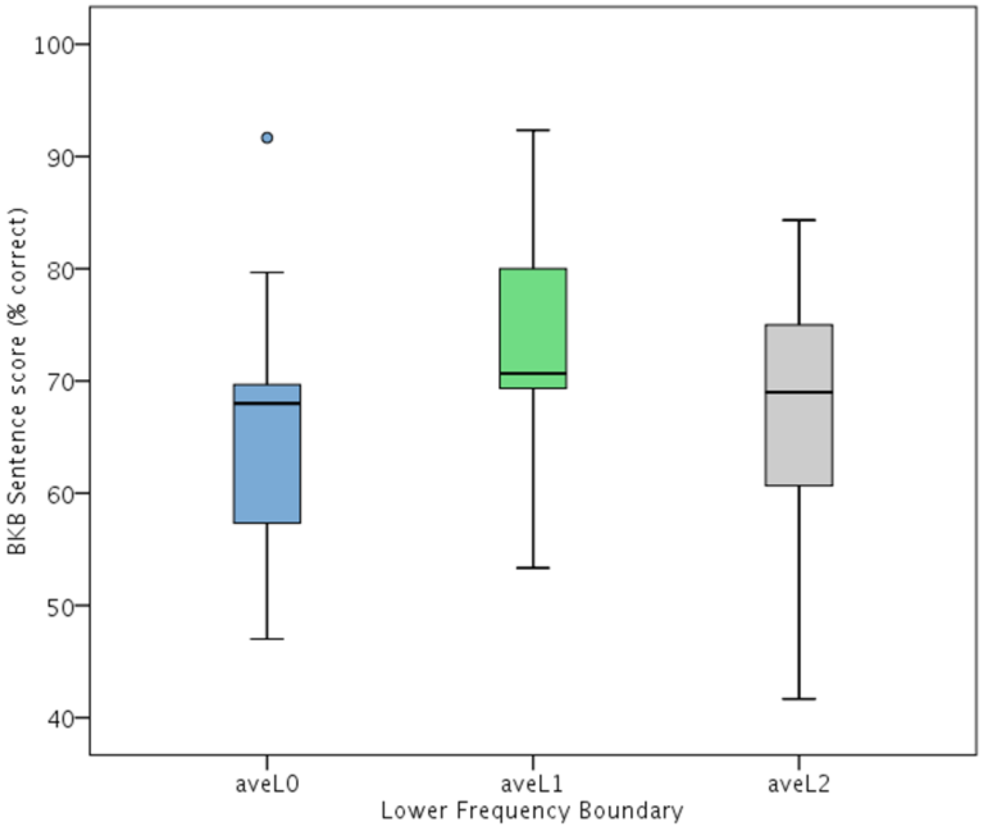


Figure 58 BKB sentence scores with different lower frequency boundaries

Mauchly's test produced a significant result [$\chi^2(2)=9.87$, $p=0.007$] when the lower frequency boundary variables (L0, L1 and L2) were compared. Repeated-measures ANOVA was performed with a between-subjects factor of PCT score for basal electrodes and the Greenhouse-Geisser correction was applied. A significant effect of lower frequency boundary was found [$F(1.23,13.5)=5.94$, $p=0.024$] but there was no interaction between the PCT score for basal electrodes and BKB sentence score with the different lower frequency boundaries [$F(1.23,13.5)=0.109$, $p>0.05$] and no independent effect of PCT score for basal electrodes [$F(1,11)=1.85$, $p>0.05$]. Pairwise comparisons with Bonferroni corrections for three comparisons indicated that L1 offered better performance than L0 [$p=0.009$, $r=0.59$] and L2 [$p=0.006$, $r=0.77$], both large effects.

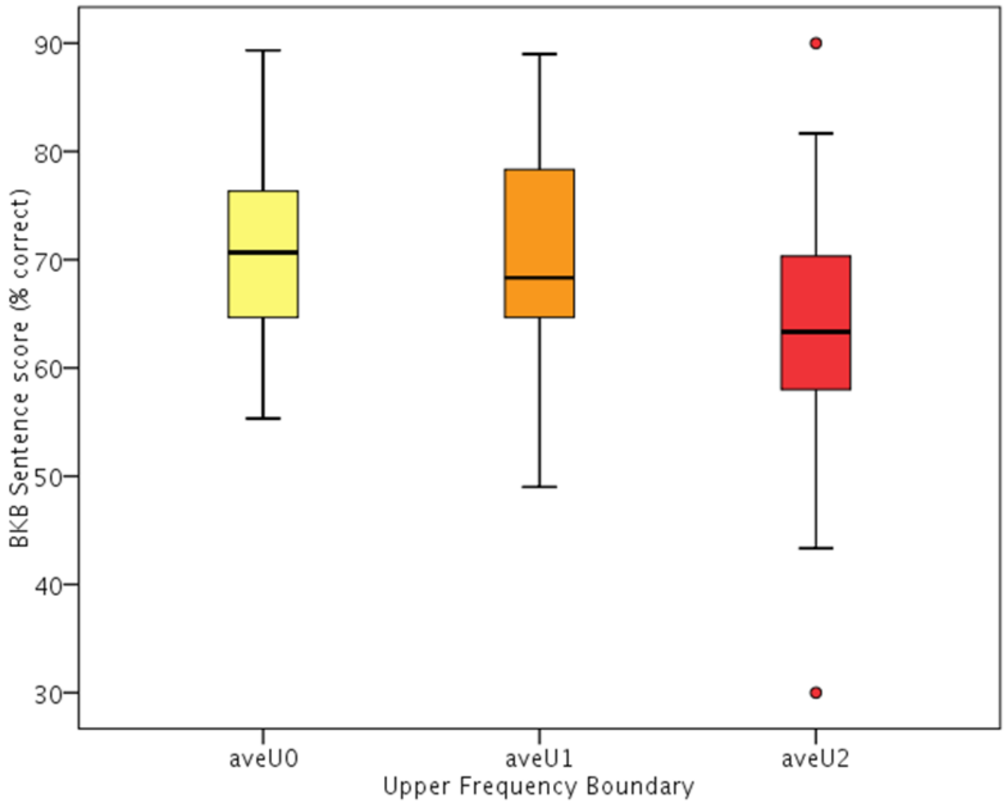


Figure 59 BKB sentence scores with different upper frequency boundaries

Similar analysis was performed to investigate the effect of upper frequency boundary on BKB sentence score. Mauchly's test again produced a significant result when the upper frequency boundaries were compared [$\chi^2(2)=7.3$, $p=0.026$]. Repeated-measures ANOVA was performed with a between-subjects effect of PCT score for basal electrodes and a Greenhouse-Geisser correction was applied. A significant main effect of upper frequency boundary was observed [$F(1.32,14.5)=6.98$, $p=0.014$]. There was also a significant interaction between PCT score for basal electrodes and performance on the BKB sentence test with different upper frequency boundaries [$F(1.32,14.5)=5.86$, $p=0.022$] but no independent effect of PCT score for basal electrodes [$F(1,11)=1.85$, $p>0.05$].

Pairwise comparisons indicated that U2 offered poorer performance than U0 [$p=0.017$, $r=0.65$, a large effect] and U1 [$p=0.02$, $r=0.63$, a large effect] across the whole group. No significant difference was found between performance with U0 and U1 [$p>0.05$]. Bonferroni corrections were not applied in this case, as this would have contradicted the outcome of the ANOVA.

Within-subjects contrasts suggested that participants with poor PCT score for basal electrodes performed worse than those with above chance PCT score for basal electrodes for upper frequency boundary U2, when compared with U0 [$F(1,11)=7.12$, $p=0.022$, $r=0.62$, a large effect], as shown in Figure 60.

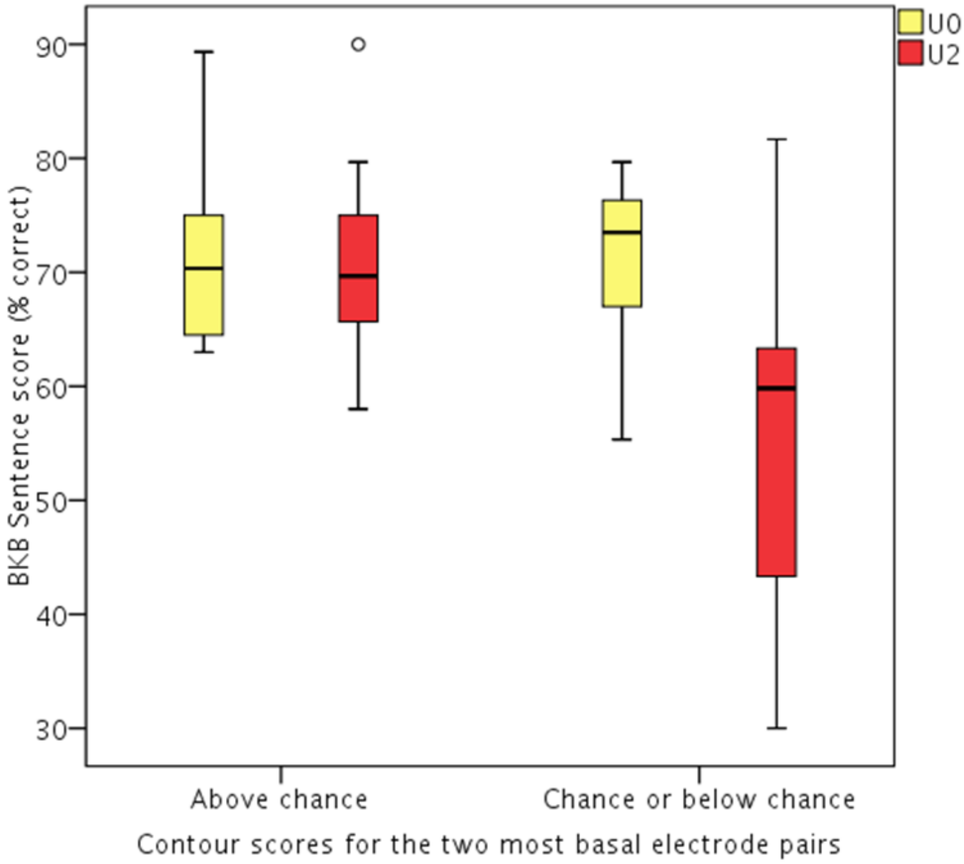


Figure 60 Effect of PCT scores for basal electrodes on BKB score with different upper frequency boundaries

Results for individual participants for the BKB sentence test were also investigated, to see if there were any individually significant improvements between scores with the default map and the study maps. Critical differences for the BKB sentence test (Martin, 1997) were used to determine if individual differences were significant or not. Some individual scores with study maps were poorer than scores for the default map, whilst others were similar and some were significantly better. The number of individual significant results for each map is shown in Figure 61.

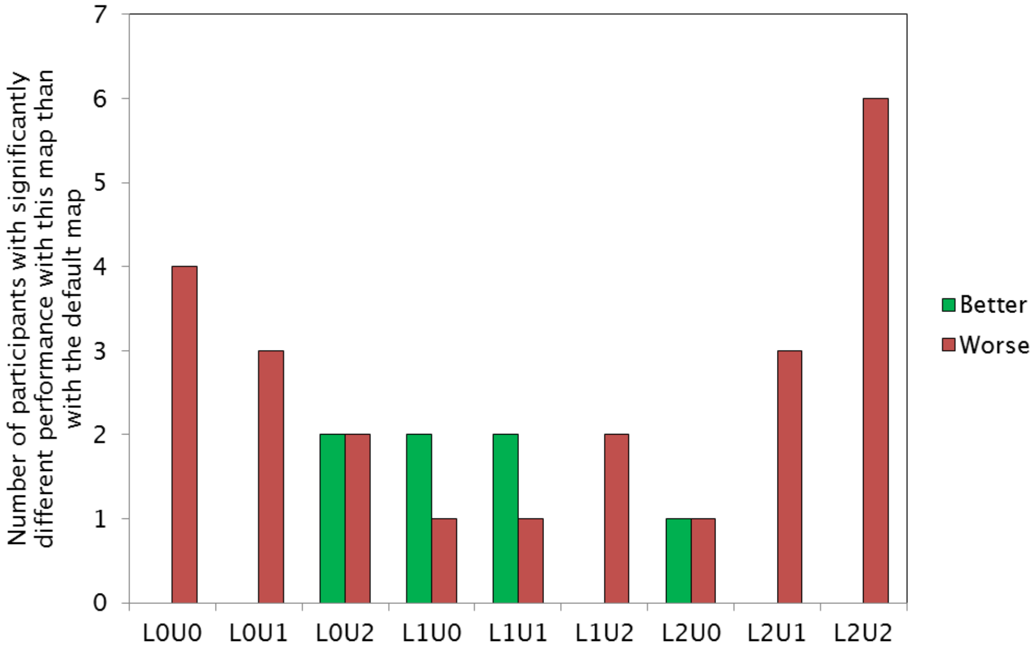


Figure 61 Individual performance on the BKB sentence test with the different maps

Of the seven maps which resulted in significant improvement compared to the default map for individual participants, five improved scores were recorded by participants with above chance scores on the PCT for all electrodes; one was recorded for a participant with chance/below chance scores at the apical end and the other was recorded in a participant with chance/below chance scores at both ends of the electrode array. The maps offering improved performance are shown in Figure 62, whilst those which did not offer improved performance are shown in Figure 63.

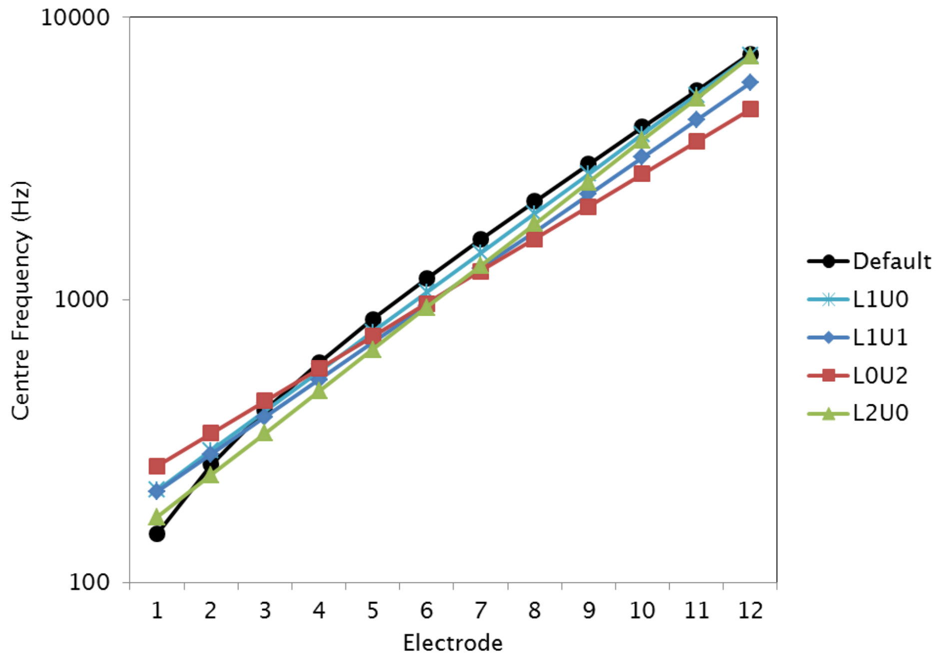


Figure 62   Frequency allocations for maps offering improved performance compared to the default for some individuals and the default

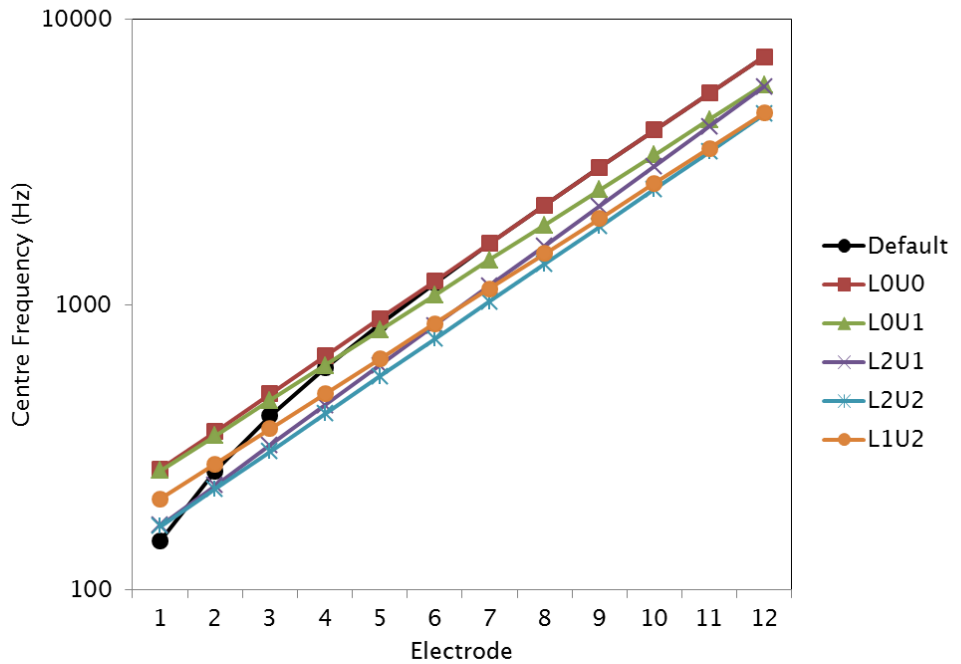


Figure 63   Frequency allocations for maps which only offered poorer or similar performance for individual participants in comparison with the default

It was observed that individual scores with the study maps were markedly different between individuals. Three examples are shown in Figure 64, Figure 65 and Figure 66, those for participants P12, P3 and P2. P12 had above chance scores on the

PCT for middle and basal electrodes but chance scores for E2E3 at the apical end. P3 had above chance scores for all electrode pairs except E11E12. P2 had above chance scores on the PCT for electrode pairs E1E2 to E9E10 but chance or below chance scores for E10E11 and E11E12.

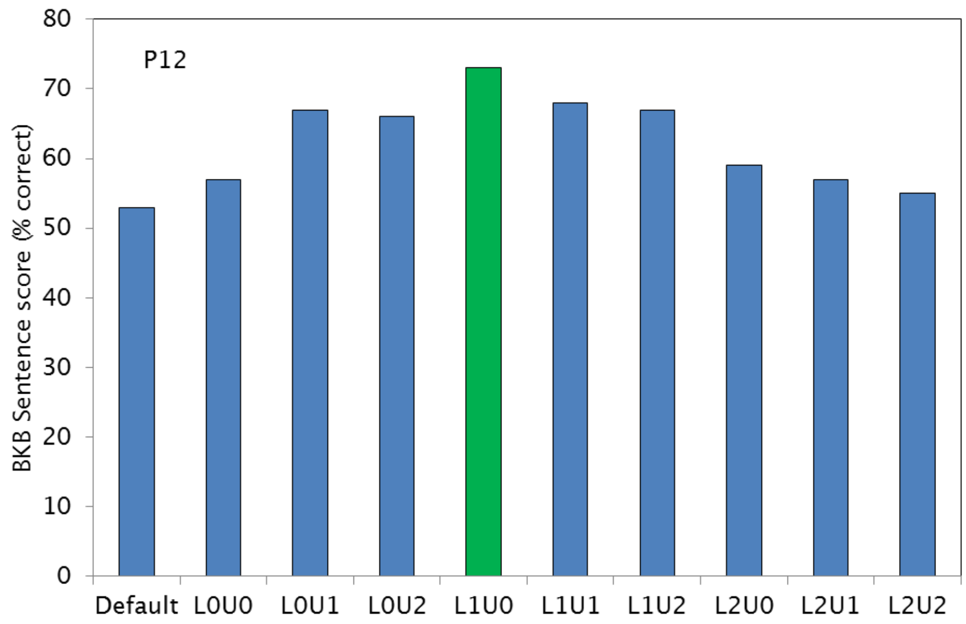


Figure 64 BKB Sentence scores for P12. The green bar indicates improved performance with this map.

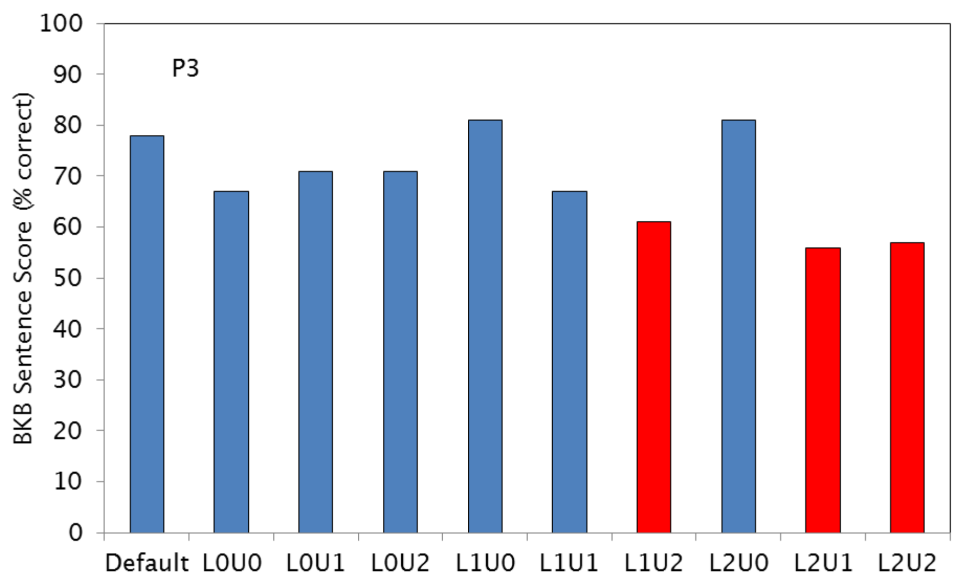


Figure 65 BKB Sentence scores for P3. The red bars indicate significantly poorer performance than for the default map.

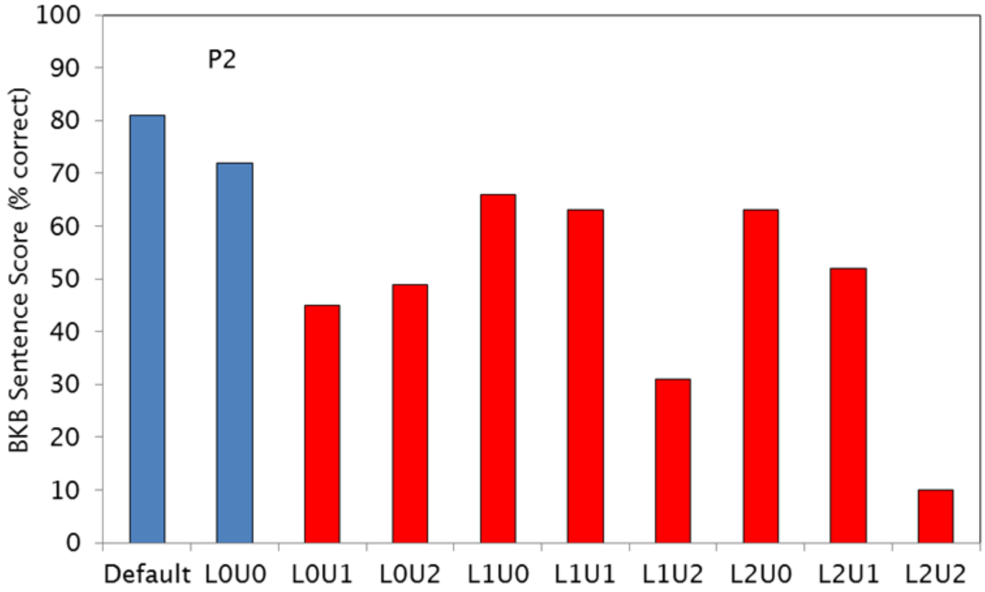


Figure 66 BKB sentence scores for P2. The red bars indicate maps which offered poorer performance than the default map.

For P2, there was a significant correlation between the frequency shift in the map when compared with the L0U0 map and scores on the BKB sentence test, as shown in Figure 67 [*r*=-0.80, *p*=0.01]. Additionally, P2's clinical data showed increased comfort levels for basal electrodes (rising to 35.8 charge units on E12, compared to 17.7 units at the apical end on E1) and increased electrical impedances (rising from 3.5 kΩ on to 10 kΩ on E10 and 9.7 kΩ on E12).

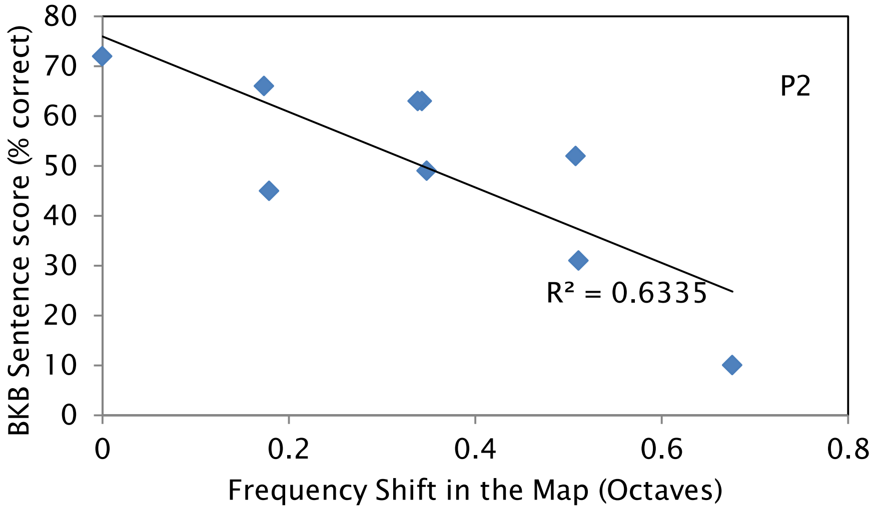


Figure 67 BKB sentence scores as a function of frequency shift from map L0U0 for participant P2.

5.3.2.1 Summary of BKB Sentence Scores

The most interesting findings related to the BKB sentence test scores were as follows:

1. It was found that maps L1U0 and L1U1 resulted in better performance than L0U0 for the group of participants; the default map did not give significantly different performance from any of these three maps.
2. There were some individual scores with study maps which were significantly better than scores for the default map. These either had minimal frequency shift compared to the default map (L1U0) or frequency shift of approximately one-third octave in the middle of the frequency range (maps L1U1, L0U2 and L2U0). These maps intersected around E6.
3. Scores were different for those with poor pitch perception for basal electrodes compared with those with good pitch perception for basal electrodes, as measured on the PCT. The effect was strongest for map L1U1.
4. The upper frequency boundary U0 offered better performance than U2. The interaction between performance on the PCT for basal electrodes and BKB sentence scores with different upper frequency boundaries, suggests that this was due to poor pitch perception rather than frequency shift or loss of frequency range.
5. The lower frequency boundary L1 offered better performance than L0 and L2. Frequency shift was minimal for E2 and E3 with the L1 maps (with frequency range approximately 250 to 400 Hz). For higher frequencies there was some basal shift. L2 maps had the greatest basal shift overall. L0 had smallest shift overall but the largest amount at the apical end. L0 maps also had the greatest loss of frequency range at apical end, although this was still limited as L0 = 225 Hz.

5.3.3 Vowel Identification Test

Vowel recognition test scores were not normally distributed for the L0U0, L0U1, L0U2, L1U0, L1U1 and L2U0 maps. Examination of the data suggests that this was due to ceiling effects, as shown in Figure 68.

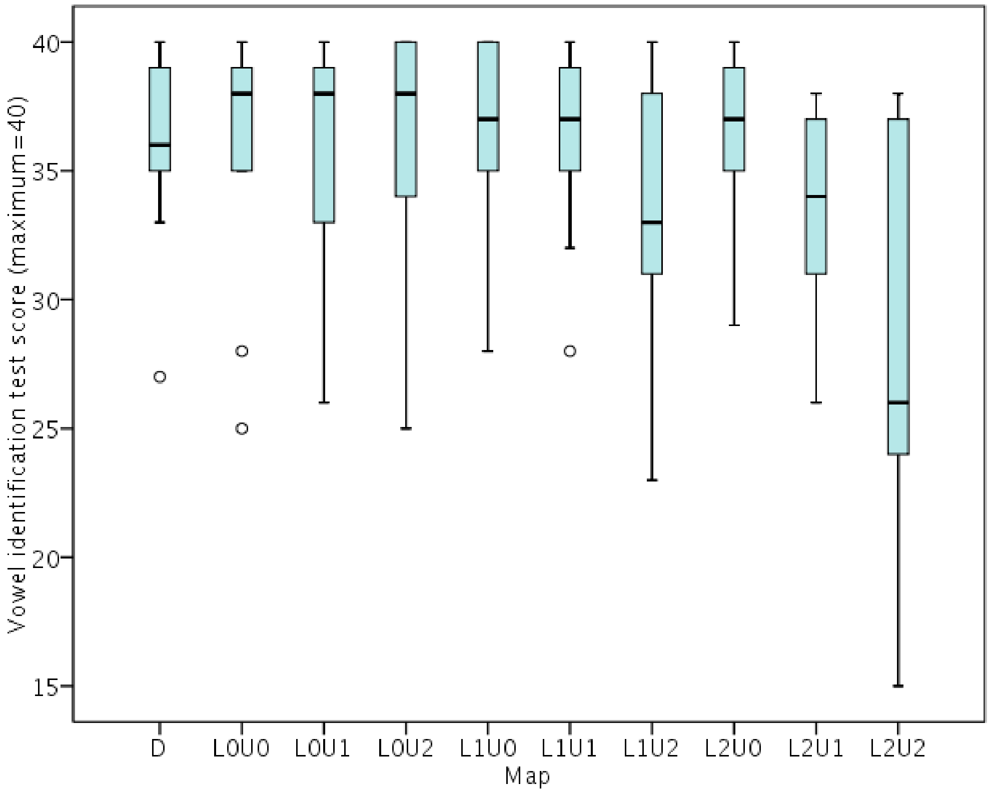


Figure 68 Vowel identification test scores for all participants and all maps

Vowel test scores were investigated using Friedman's test. This test does not allow for between-groups interactions within the analysis, so it was not possible to investigate the effect of PCT score with this test. A significant effect of map on vowel test score was found [$\chi^2(9)=40.8$, $p<0.001$]. Wilcoxon's signed ranks tests suggested that the L2U2 map offered poorer performance than the L0U0 map [$Z=-2.94$, $p=0.027$, $r=-0.58$, a large effect] but none of the other maps offered significantly different performance when compared with the L0U0 map. Bonferroni corrections were applied for nine comparisons.

To see if this difference was related to basal shift, the analysis was repeated for the participants with above chance scores for the PCT for basal electrodes (who were assumed to have no pitch perception difficulties at the basal end). Friedman's test was repeated. A significant effect of map on vowel test score was found [$\chi^2(9)=20.4$, $p=0.016$]. Again, Wilcoxon's signed ranks tests suggested that the L2U2 map offered poorer performance than the L0U0 map [*Z*=-2.023, *p*=0.043, *r*=-0.54, a large effect] but none of the other maps offered significantly different performance when compared with the L0U0 map. Bonferroni corrections were not applied, as this would have been inconsistent with the result of Friedman's test. This suggested that there was an effect of basal shift for this map. Test scores for these participants are shown in Figure 69.

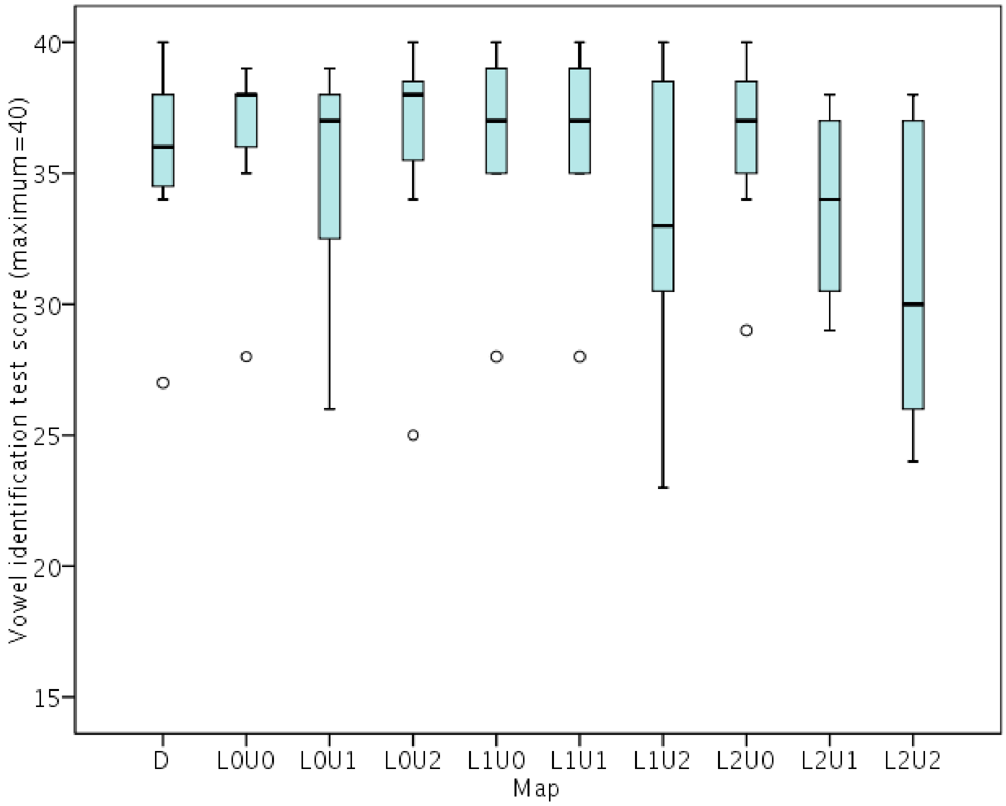


Figure 69 Vowel identification test scores for the seven participants with above chance scores for basal electrodes for the PCT

To investigate the effect of the lower and upper boundaries separately, new variables were calculated. All participants were included in this part of the analysis. The maps with lower boundary L0 (L0U0, L0U1 and L0U2) were averaged to make a new variable L0 and similarly for the other boundaries, as shown in Figure 70. The L0 and U0 maps were not normally distributed so the boundaries were investigated using Friedman's test. A significant effect of lower boundary was found [$\chi^2(2)=7.04$, *p*=0.03]. Wilcoxon's signed ranks test, with Bonferroni corrections for three comparisons applied, indicated that L2 offered poorer performance than L0 [*Z*=-2.69, *p*=0.021, *r*=-0.53] and L1 [*Z*= -2.84, *p*=0.015, *r*=-0.56], both large effects. There was no significant difference in performance between L0 and L1 [*Z*=-0.665, *p*>0.05].

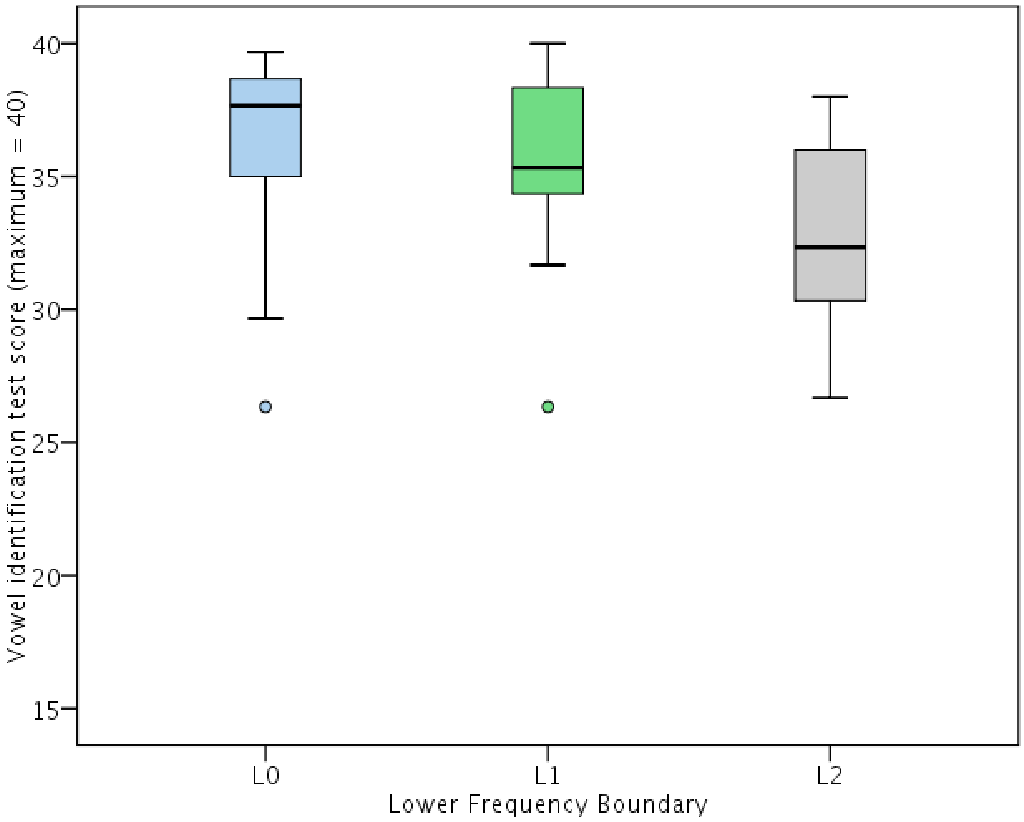


Figure 70 Vowel identification test scores with different lower frequency boundaries

A significant effect of upper frequency boundary on vowel recognition score was also found using Friedman's test [$\chi^2(2)=11.8$, $p=0.003$]. Wilcoxon signed ranks test, with Bonferroni corrections for three comparisons applied, indicated that U2 offered poorer performance than U0 [$Z= -2.70$, $p=0.021$, $r=-0.53$] and U1 [$Z = -2.67$, $p=0.024$, $r=-0.52$], both large effects. There was no significant difference in performance between U0 and U1 [$Z=-1.91$, $p=0.056$]. Vowel test scores with the different upper frequency boundaries are shown in Figure 71.

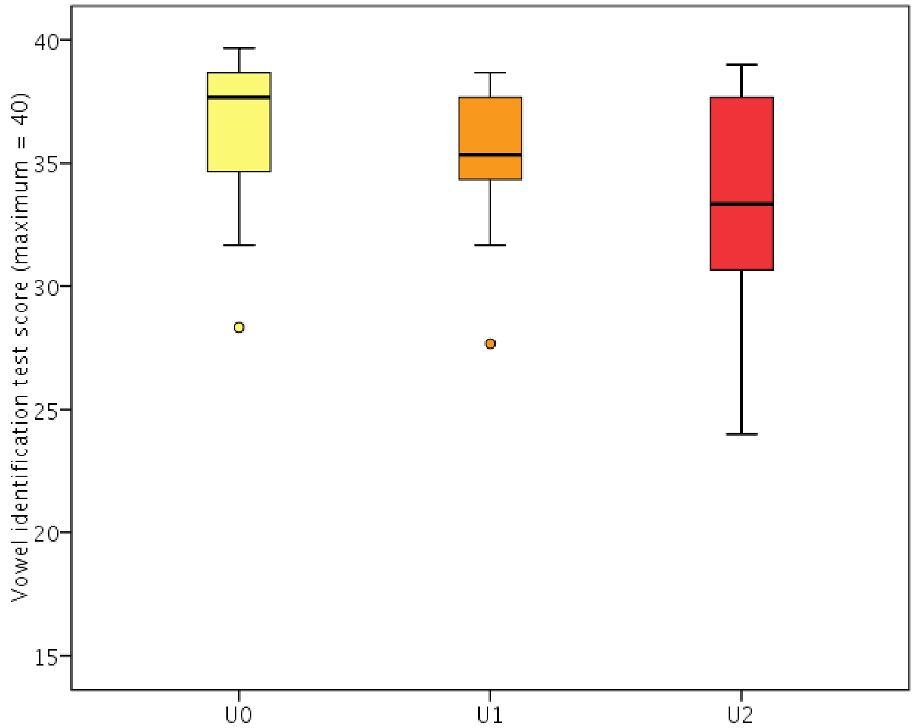


Figure 71 Vowel identification test scores with different upper frequency boundaries.

The pattern of errors was analysed for the vowel recognition test, as shown in Table 12.

Table 12 Vowel confusion matrix for all maps and all participants shown as percent correct: presented tokens are shown in the first column and perceived tokens in the first row. Orange shaded boxes pertain to the correct answer.

Totals	Had	heard	hard	heed	hood	who'd	Hid	head
had	99	0	0	0	0	0	0	1
heard	1	88	10	0	0	1	0	0
hard	3	32	65	1	0	0	0	0
heed	0	0	0	80	1	17	1	0
hood	0	0	0	0	87	1	9	1
who'd	0	1	0	10	2	87	0	0
hid	0	0	0	0	5	0	93	1
head	2	0	0	0	0	0	2	96

It was found that ‘heard’ and ‘hard’ were most commonly confused. There was a tendency for ‘hard’ to be perceived as ‘heard’, which has slightly higher F2 but lower F1.

For map L2U2, for which performance was worse than for L0U0, the error patterns were also analysed, and are shown in Table 13.

Table 13 Vowel confusion matrix for map L2U2, show as percent correct: presented vowels are shown in the first column; perceived vowels are shown in the first row. Orange shaded areas pertain to the correct answer.

Totals	had	heard	hard	heed	hood	who'd	Hid	Head
had	100	0	0	0	0	0	0	0
heard	5	58	34	0	0	3	0	0
hard	18	31	43	8	0	0	0	0
heed	0	2	0	38	11	43	5	2
hood	2	0	0	0	65	8	8	11
who'd	0	3	0	14	5	77	0	2
hid	0	0	0	2	31	0	62	6
head	6	0	2	0	0	0	2	91

It was found that scores were poorest for ‘heed’ which was more often perceived as ‘who’d’. ‘Who’d’ has similar F1 but lower frequency F2.

5.3.3.1 Summary of Vowel Identification Test Scores

1. A ceiling effect was found for the majority of frequency allocations with this test.
2. Vowel identification was poorer for the L2U2 map than the L0U0 map. This was assumed to be due to basal shift, as it applied to participants with good pitch perception at the basal end when their data was analysed separately.
3. Frequency boundaries L2 and U2 offered poorer performance than L0, L1, U0 and U1. Use of L2 increased the frequency range at the low frequency end whilst U2 reduced the frequency range at the high frequency end. L2 and U2 were associated with larger amounts of basal shift relative to the default map than the other frequency boundaries.

4. The stimuli ‘hard’ and ‘heard’ were most commonly confused in the test. Vowel formants for these tokens are relatively close when visualised in the vowel space shown in Figure 53.
5. For the L2U2 map, ‘heed’ was more often perceived as ‘who’d’, which has similar F1 but lower frequency F2. The vowel ‘heed’ when heard with the default map stimulates the same electrodes as the token ‘who’d’ when heard with the L2U2 map.
6. P1 was an outlier on this test, giving poorer results for some maps than other participants. P1 confused ‘who’d’ and ‘heed’ and ‘hood’ and ‘hid’ more often than not.

5.3.4 Music Assessments

5.3.4.1 Familiarity with the Song for the Music Rating

Participants were asked if they were familiar with Sir Cliff Richard's song, 'We don't talk anymore.' Eight participants reported being familiar with the song; participants P5, P8 and P9 reported that they were not previously familiar with it. These three participants listened to the song with their everyday map before listening with the study maps (which included the default map). None of them were found to be outliers on any of the measures described below, so their data were included in the data for the whole group (outliers were defined as being at a distance of 1.5*inter-quartile range from the inter-quartile range or greater).

5.3.4.2 Natural sound quality for each map

Participants were asked to rate the sound quality of the music from unnatural (=0) to natural (=1), on a visual analogue scale. Ratings are shown in Figure 72. All ratings were found to be normally distributed (Shapiro-Wilk $p>0.05$).

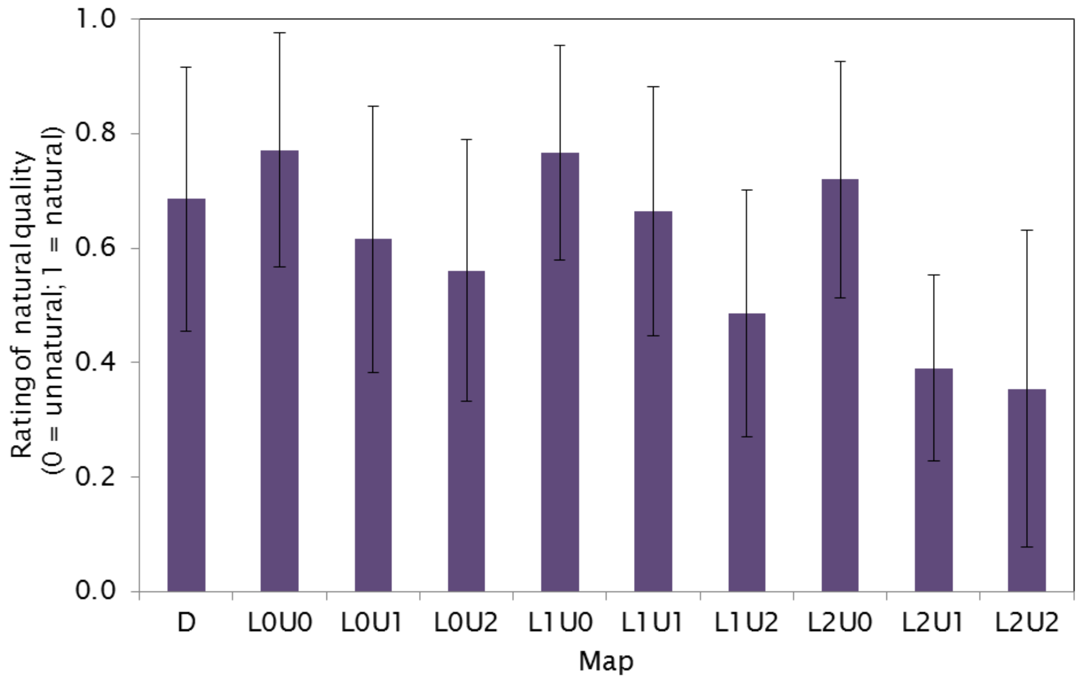


Figure 72 Natural sound quality ratings for each map; bars represent the mean, error bars the standard deviation. 'D' is the default map.

The effect of map on the rating of natural sound quality was investigated using repeated-measures ANOVA. As there were only eleven participants who took part in this part of the study, it was not possible to analyse the data for different groups based on PCT scores for apical and basal electrodes, according to performance on the PCT, as it was for the BKB sentence test. However, it was possible to include one of these, so the group with poor performance at the basal end on the PCT was analysed (N=4 for this group). The assumption of sphericity was met (Mauchly's test of sphericity $\chi^2(44)= 37.2$, $p=0.933$). A significant main effect of map was found [$F(9,81)=7.56$, $p<0.001$]. There was no interaction between natural rating and PCT score for basal electrodes [$F(9,81)=1.34$, $p>0.05$] but there was an independent effect of PCT score for basal electrodes [$F(1,9)=5.84$, $p=0.039$, $r=0.63$, a large effect], indicating that those with poor pitch perception for basal electrodes rated the song differently from those with good perception. Ratings for the two groups are shown in Figure 73. It can be seen that those with poor pitch perception for basal electrodes rated the sound as more natural than those who did not. This is an unexpected result and may be due to the low number of participants in the group with poor pitch perception at the basal end (N=4).

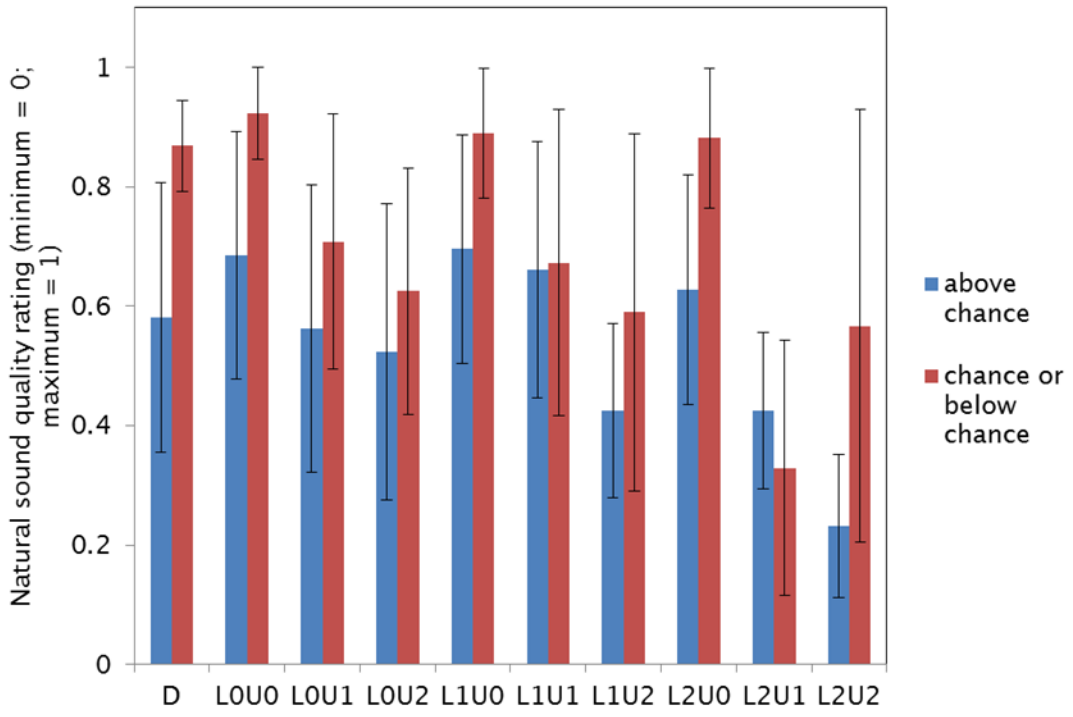


Figure 73 Mean natural sound quality ratings for participants with above chance or at/below chance scores on the PCT for basal electrodes

As map L0U0 was the most apical map, and had uniform (logarithmic) frequency spacing, in common with the other alternative maps, comparisons between this map and the other maps were made. A pairwise comparison indicated that the default map did not have a significantly different rating from the L0U0 map (*p*>0.05). Pairwise comparisons (Bonferroni corrected, based on nine comparisons) suggested that the L1U2, L2U1 and L2U2 maps were significantly less natural than L0U0 [*p*=0.036, *r*=0.79; *p*<0.01, *r*=0.87 and *p*<0.01; *r*=0.83 respectively]. These maps had the greatest frequency shift from the L0U0 map. To investigate the effect of frequency shift on the naturalness of the sound quality further, the amount of frequency shift was correlated with the natural quality rating, as shown in Figure 74. This was averaged over all participants.

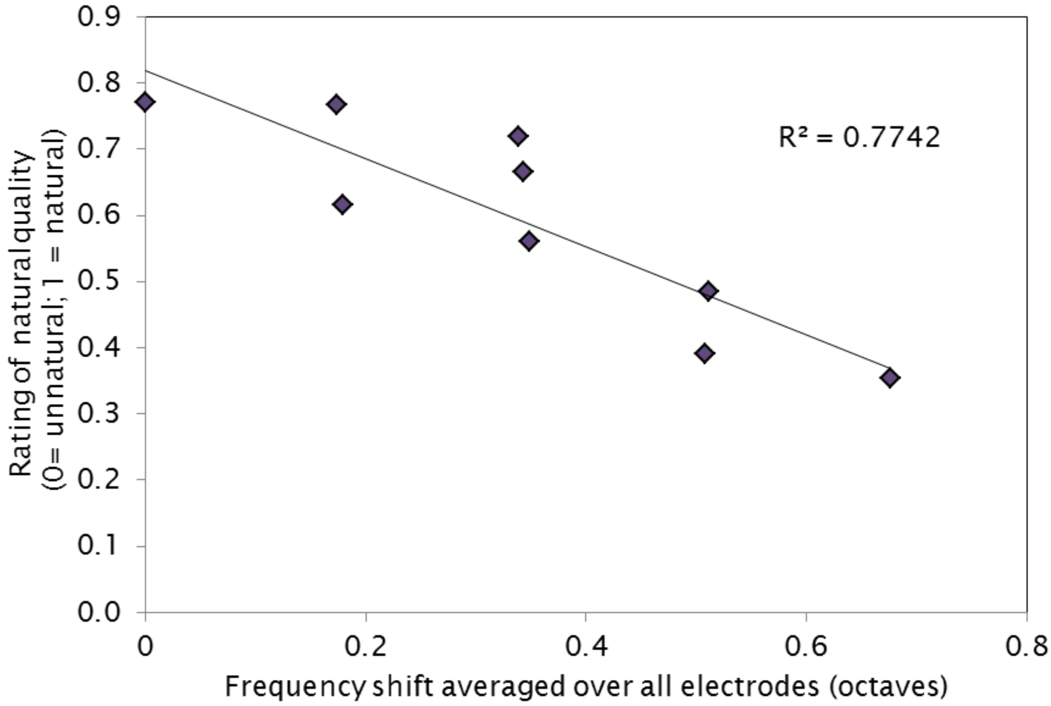


Figure 74 Correlation of natural sound quality rating and the frequency shift from the L0U0 map, averaged over all participants and electrodes

A significant correlation was found between the frequency shift in the map and the rating of natural sound quality [*r*=-0.881, *p*=0.002, 2-tailed]. The default map was not included in this comparison as it had non-uniform frequency spacing, unlike the other maps.

To investigate the effect of frequency shift at the apical end separately from frequency shift at the basal end, new variables were computed for each lower and upper frequency boundary setting, which were averaged over the corresponding maps (so, for example, the rating for map L0 was the average rating for maps L0U0, L0U1 and L0U2). The new variables L0, L1, L2, U0, U1 and U2 were all normally distributed and had natural sound quality ratings as shown in Figure 75.

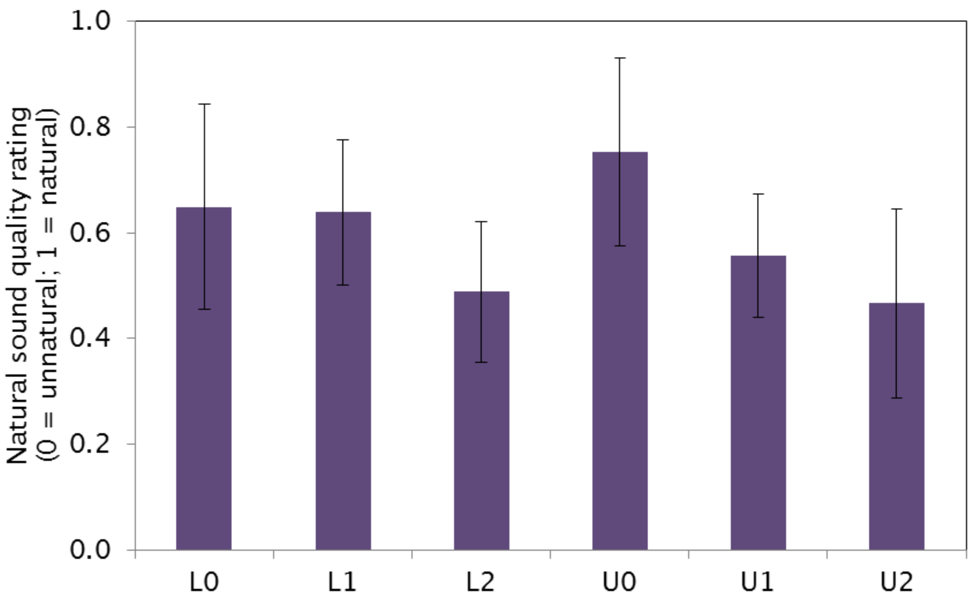


Figure 75 Natural sound quality ratings as a function of lower or upper frequency boundary

The effect of lower frequency boundary was investigated using ANOVA. The condition of sphericity was met [Mauchly's test $\chi^2(2)=0.357$, $p=0.836$]. A significant main effect of lower frequency boundary was found, [$F(2,20)$]=7.18, $p=0.004$]. Pairwise comparisons showed that the L0 condition was more natural than the L2 condition [$p=0.011$, $r=0.76$] with a Bonferroni correction for three comparisons applied). The L1 condition was also rated significantly different from L2 [$p=0.044$].

Similarly, the effect of upper frequency boundary was investigated using ANOVA. Mauchly's test [$\chi^2(2)=0.093$, $p=0.955$] A significant main effect of upper frequency boundary was found [$F(2,20)=16.6$, $p<0.001$, $r=0.67$]. Pairwise comparisons (Bonferroni corrected for three comparisons) showed that U0 was more natural than both U1 [$p=0.011$, $r=0.77$] and U2 [$p=0.001$, $r=0.87$]; U1 was not significantly different from U2 ($p>0.05$).

5.3.4.3 Judgment of Pitch

Participants were asked 'Do you think that the pitch is correct?' and rated it from very low (=-1) to very high (=1) on a visual analogue scale. To check that they had understood this task correctly, the data were examined. It was anticipated that participants would rate the majority of maps as being higher in pitch than the L0U0 map and, in particular, that the shifted maps L1U1 and L2U2 would be rated as higher in pitch than L0U0. Results for individual participants are showed that all participants appeared to have rated the maps appropriately, except for P13, who had said that the pitch was lower than expected rather than higher than expected. P13's data was therefore excluded from the analysis related to the rating of whether the pitch was correct. Ratings for the remaining participants are shown in Figure 76.

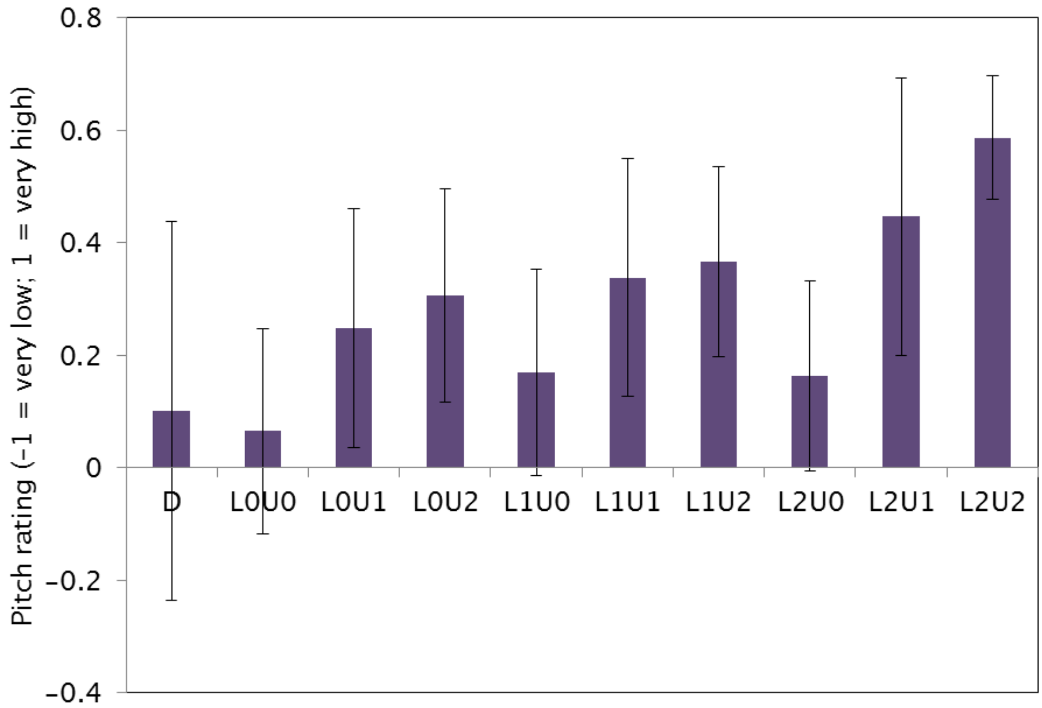


Figure 76 Pitch ratings for the different maps

The effect of map frequency allocation on the pitch rating was investigated by repeated-measures ANOVA, as all variables were normally distributed. Mauchly's test gave a non-significant result [$\chi^2(44) = 53.3$, p=0.345]. There were insufficient participants to include the PCT results as a factor in the analysis for this rating. A significant main effect of map was found [$F(9,81)=6.69$, $p<0.001$]. Pairwise comparisons showed that there was no significant difference in pitch rating between the default and L0U0 conditions. When compared with the L0U0 condition, with Bonferroni corrections for nine comparisons applied, it was found that maps L0U2, L1U2 and L2U2 were rated as significantly higher in pitch than the L0U0 condition [p=0.045, r=0.78; p=0.009, r=0.84 and p<0.001, r=0.95 respectively]. In addition, a significant correlation was found between the frequency shift from the L0U0 map and the average rating of pitch across the ten participants included in the analysis [r=0.924, p<0.001, 2-tailed], as shown in Figure 77. The default map was excluded from this analysis on account of its non-uniform frequency spacing.

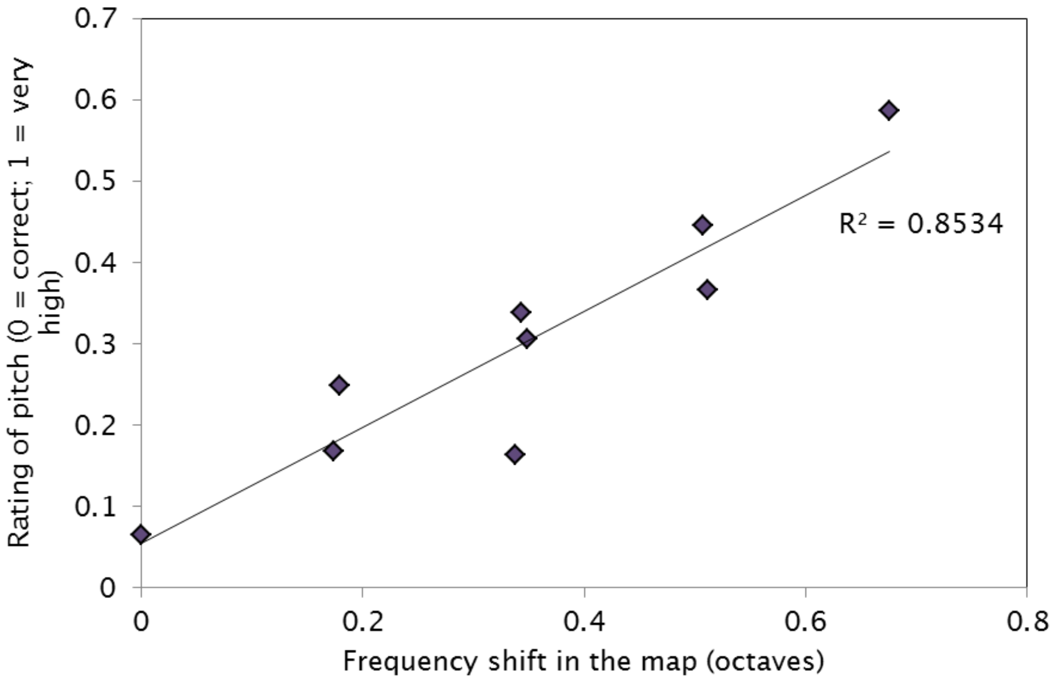


Figure 77 Subjective ratings of 'pitch correct'

To investigate the effect of the lower and upper boundaries separately, new variables were computed: the average pitch rating for each of the conditions L0, L1, L2, U0, U1 and U2 was computed from the corresponding maps for these ten participants. Ratings for these new variables are shown in Figure 78.

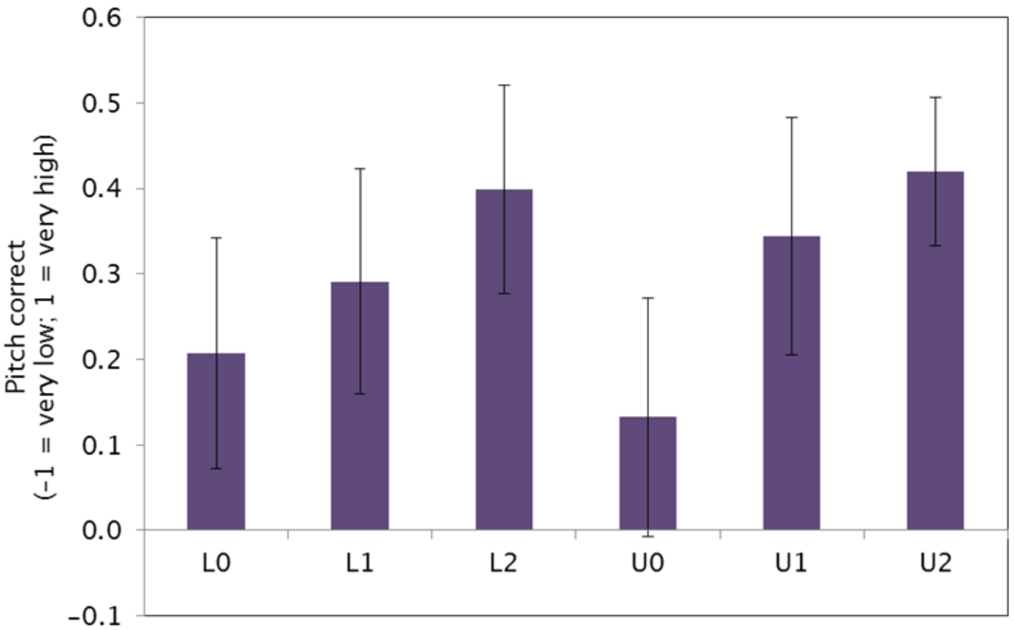


Figure 78 Ratings of 'pitch correct' as a function of lower and upper frequency boundaries

The effect of lower frequency boundary was analysed using ANOVA, as the new variables were normally distributed [Mauchly's test of sphericity $\chi^2(2) = 0.653$]. A significant main effect of lower frequency boundary was found [$F(2,18)=7.42$, $p=0.004$]. Pairwise comparisons, with a Bonferroni correction for three comparisons, showed that the L2 condition was rated as significantly higher in pitch than the L0 condition [$p=0.019$, $r=0.76$]. The L1 condition was not rated significantly differently from either of the other two conditions ($p>0.05$).

The upper frequency boundary was also analysed using ANOVA, as the new variables were normally distributed (Mauchly's test of sphericity [$\chi^2(2)=2.79$]). A significant main effect of upper frequency boundary was found [$F(2,18)=21.5$, $p<0.001$]. Pairwise comparisons, with a Bonferroni correction for 3 comparisons, showed that the U1 and U2 conditions were rated as significantly higher in pitch than the U0 condition [$p=0.013$, $r=0.78$ and $p<0.001$, $r=0.94$ respectively] but the difference between the U1 and U2 conditions was not significant ($p>0.05$).

5.3.4.4 Clarity of the Lyrics

Participants were asked if the lyrics were clear and rated the lyrics between unclear (=0) and clear (=1), on a visual analogue scale. Ratings for the clarity of the lyrics were not found to be normally distributed for the default, L0U1, L0U2 and L1U1 maps. Ratings are shown in Figure 79.

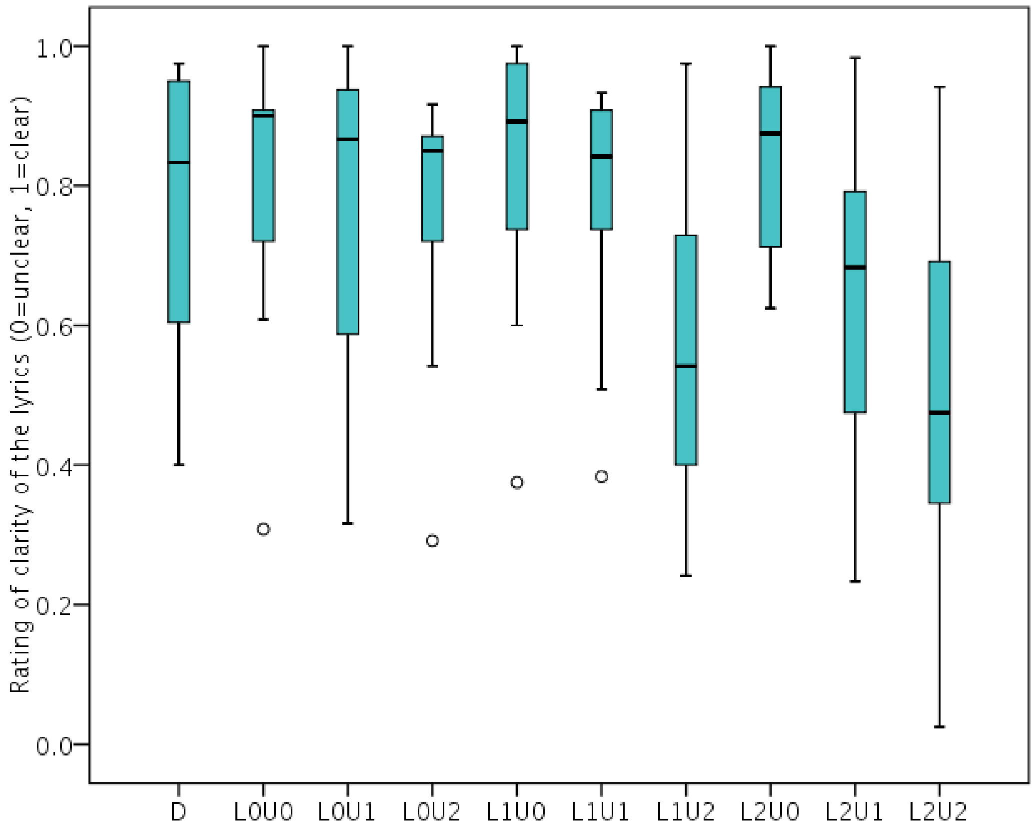


Figure 79 Rating of clarity of the lyrics for the song presented for the music assessment with the different study maps

Friedman's test was used to investigate the effect of map on the clarity of the lyrics. A significant effect of map was found [$\chi^2(9)=25.0$, $p=0.003$]. No significant difference was found between the clarity of the lyrics for the default and L0U0 maps, when tested with Wilcoxon's signed ranks test [$Z=-0.267$, $p>0.05$]. The remaining maps were compared with the L0U0 map: in this case Bonferroni corrections for nine comparisons were not applied, as this would have been inconsistent with the result of Friedman's test. Wilcoxon's signed ranks test suggested that the lyrics of the L1U2 and L2U2 maps were less clear than those of the L0U0 map [$Z=-2.09$, $p=0.037$, $r=0.45$, a medium effect for L1U2 and $Z=-2.536$, $p=0.011$, $r=0.54$ for the L2U2 map, a large effect].

5.3.4.5 Adjustment of Pitch

Participants were asked to adjust the pitch using the slider to correct it, for those maps for which they had rated it as incorrect. It was anticipated that participants would reduce the pitch of the song for the majority of maps, and specifically the maps L1U1 and L2U2 would be adjusted downwards relative to map L0U0, if participants had understood the task correctly. From examination of the data, it was found that all participants, except P3, had adjusted the pitch slider appropriately. P3 appeared to find this task difficult, at first, and moved the pitch slider in the wrong direction for three out of four maps in her first session. The results from her second session are much more similar to those for other participants and to her data for the rating of pitch. However, in view of the inconsistency, P3's results were excluded from this part of the data analysis, leaving data for ten participants, as shown in Figure 80. It was found that the data for the default and L1U2 maps were not normally distributed (Shapiro-Wilk $p<0.05$).

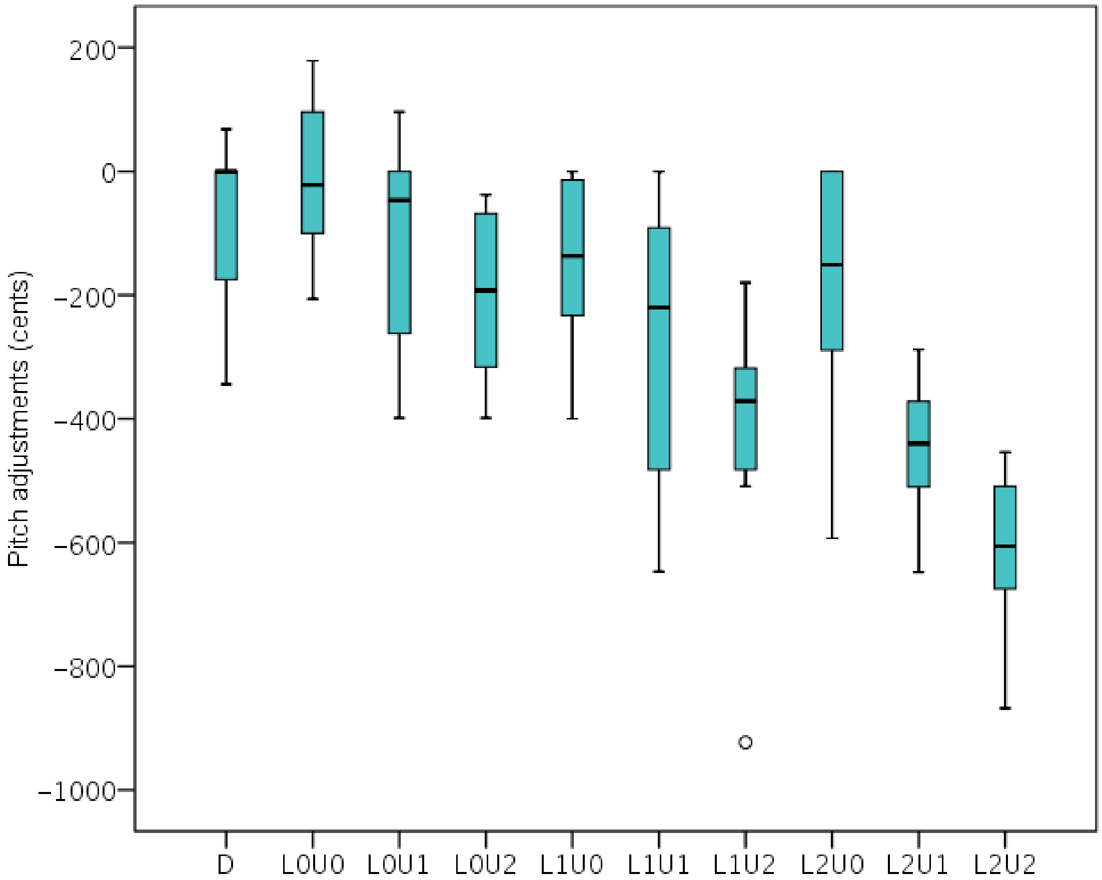


Figure 80 Pitch adjustment for the 10 participants included in the analysis for the study maps

For the L1U2 map, the lack of normality appeared to be due to an outlier (P1). The default and L1U2 map was compared to the L0U0 map using Wilcoxon's signed ranks test, in view of this finding. The default map was not significantly different from the L0U0 map [Z=-0.770, p>0.05]. The remaining maps were compared using repeated-measures ANOVA, as the conditions were met for all but the L1U2 map. Mauchly's test showed that the condition of sphericity was met [$\chi^2(35)=38.9$, $p=0.453$]. A significant main effect of map was found [$F(8,72)=20.8$, $p<0.001$].

Pairwise comparisons, with a Bonferroni correction for eight comparisons applied, showed that the pitch adjustment for maps L0U2, L1U1, L1U2, L2U1 and L2U2 was significantly greater than that for map L0U0 [p=0.011, r=0.83; p=0.031, r=0.79; p=0.001, r=0.90; p<0.001 r=0.96 and p<0.001, r=0.98] respectively. 'r' was calculated from the F-ratio for within-subjects contrasts for these comparisons.

When the frequency shift in the map was compared with the average pitch adjustment for each map in cents (with the default map excluded), averaged over ten participants, a very strong correlation was observed (r=-0.968, p<0.001, 2-tailed), as shown in Figure 81. However, it was found that the magnitude of the pitch adjustment was smaller than the frequency shift in the map.

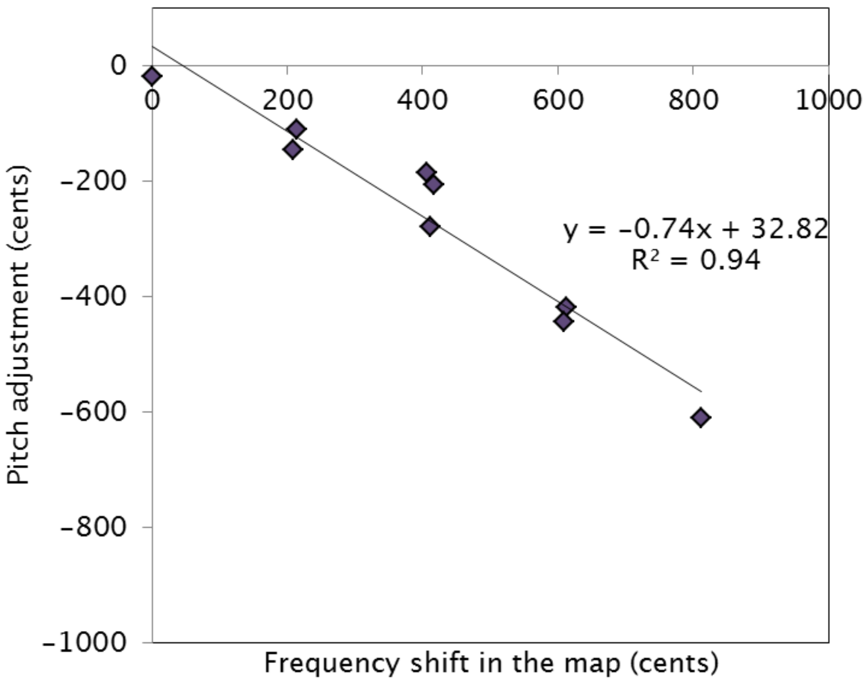


Figure 81 Correlation between frequency shift for each map and the average pitch adjustment for the map

Summary of IMAP Results:

Main findings:

1. The naturalness of the sound quality of music was found to be affected by frequency shifts within the participants' maps for these CI users: as the frequency shift increased, the music was rated as sounding less natural.
2. Post-lingually deafened adults were able to rate pitch as being too high or too low appropriately in most cases, when their maps were adjusted.

3. Similarly, the majority of participants were able to correct pitch in the appropriate direction in response to the frequency shift in the map.
4. The default allocation was rated as having close to correct pitch on average (rated as 0.1 on a scale from 0 to 1) and the median pitch adjustment for the default map was zero.
5. Naturalness of the sound quality appeared to be influenced more by electrodes four to six than electrodes one to three, as indicated by the fact that L0 is rated as similar to the default map but more natural than L2.
6. For the majority of maps, the lyrics were found to be reasonably clear (median rating >0.8 for 7 out of 10 maps). For the maps with greatest basal shift, the lyrics were reported as less clear.
7. There was a very strong correlation between the frequency shift in the map and the average pitch adjustment made (r=-0.968). This was higher than for the rating of 'pitch correct'.
8. The amount of adjustment was less than expected: around 0.75 of the amount of frequency shift.

5.4 Discussion

5.4.1 BKB Sentence Test Scores

There were seven instances where significant improvements in performance were seen with alternative maps on the BKB sentence test in experiment 2. The maps which offered improved performance either had limited shift (L1U0) or shift of one-third of an octave when compared to the L0U0 map. For the L1U0 map, the improvement may be due to a reduction in the frequency range assigned to the most apical electrodes. For the other maps, the basal shift and/or the reduction in the frequency range assigned to the apical electrodes may be responsible.

P4, P5, P8 and P10 obtained benefit from the maps with basal shift of one-third of an octave when averaged over the frequency range. The frequency allocations for these maps intersect around E6 and are shown in Figure 62. They occupy the space between the maps in Figure 63 at E5. This suggests that participants may have benefitted from a limited amount of basal shift around this point. The centre frequency for the default map on E5 is 855 Hz. The maps L2U0, L1U1 and L0U2 have centre frequencies of 668, 706 and 745 Hz at this point. These frequencies would have moved along the electrode array by one electrode or less. There is a possibility that the improvement may be due to these frequencies becoming easier to discriminate. However, this is not obvious from the PCT results, as all these participants had ceiling scores on the test for their middle electrodes.

Performance with the RFR map in experiment 1 part 2 improved for some participants with poor electrode discrimination at the apical end of the array. It might have been anticipated that there would be an interaction between BKB sentence scores in experiment 2 and PCT scores for apical electrodes. Instead, there was an interaction between BKB sentence scores and performance on the PCT for basal electrodes. This may be because performance at the basal end of the array was actually poorer than performance at the apical end of the array in experiment 2 and the basal shift had a negative effect on BKB scores. Or, it could be that frequencies allocated to the most basal electrodes in this experiment were more important for speech perception than the frequencies assigned to the apical electrodes, especially for the U2 maps. It is also likely that electrode discrimination at the apical end of the array was worse for some participants in experiment 1 when compared to participants in experiment 2 (compare results for electrode pair E2E3).

Participants P11, P12 and P13 also took part in experiment 1. The results for P13 do not appear to be completely consistent between the experiments. In experiment 1, P13 showed benefit from the RFR map in experiment 1 part 2 but not from the alternative maps in experiment 2. However, it should be noted that this participant had a different default map in experiment 2 compared to experiment 1, with a different processing strategy (FS4).

5.4.2 Vowel Test

As there was a ceiling effect for this test for the default map, it was not possible to measure improvements in mean performance across the group for the alternative maps. Performance with the default map was similar to that with the L0U0 map, whilst performance with the L0U0 map only differed significantly from that of the L2U2 map. The L2U2 map offered poorer performance than the L0U0 map and had the greatest basal shift from it.

Investigation of the lower frequency boundary gave a different result for the vowel test from the results for the sentence test. With the sentence test, L1 offered better performance than L0 and L2. With the vowel test, performance with L1 was similar to that of L0; only L2 offered poorer performance. Due to the ceiling effect with the vowel test, it is uncertain if the L0 and L1 maps do truly offer similar performance on this test. However, it is clear that performance with the L2 maps was poorer and this suggests that participants had been adversely affected by the basal shift on electrodes three to six with these maps (frequencies 300 to 900 Hz approximately). A comparison of the centre frequencies for the U1 maps and the default map for the apical half of the electrode array is shown in Figure 82.

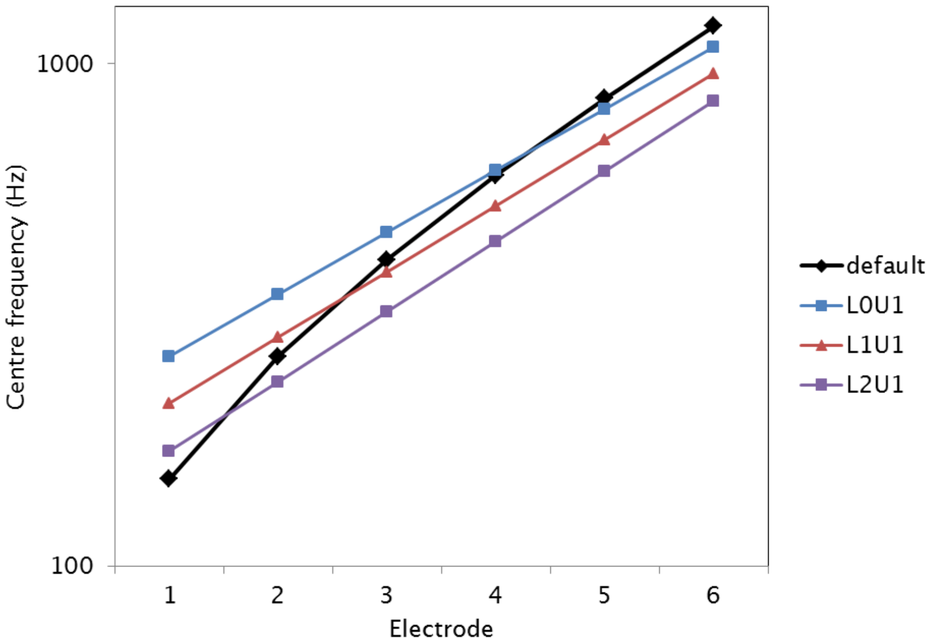


Figure 82   Map centre frequencies with U1 maps for electrodes one to six

Results for the upper frequency boundaries showed a similar pattern for the vowel and sentence tests, in that U2 offered poorer performance than U0 and U1. With the sentence test this appeared to be due to poor pitch perception for basal electrodes. However, for the vowel tests, the L2U2 map was associated with the poorest performance, even for those with above chance scores on the PCT at the basal end, suggesting an effect of spectral shift. It may be that the vowel test was more sensitive to the effect of spectral shift than the sentence test.

Performance for the individual tokens was analysed, in order to see which vowels were confused most commonly. Performance on the test for the tokens ‘hard’ and ‘heard’ is shown in Figure 83.

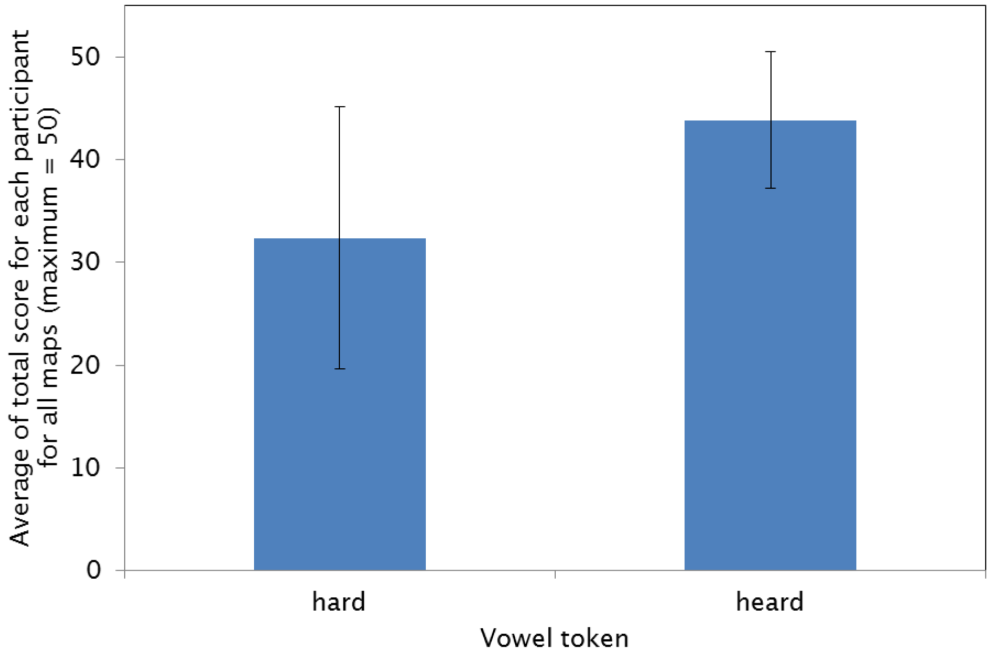


Figure 83 Scores for the vowel tokens 'hard' and 'heard' averaged across participants

The token which offered poorest performance was 'hard', which was often confused for 'heard'. It is possible to see that performance for 'heard' was better than performance for 'hard' [Wilcoxon signed ranks test Z=-2.803, p=0.005, r=-0.63]. In total there were 65 instances where the token 'heard' was perceived as 'head' and 208 instances where the token 'head' was perceived as 'heard'. The frequency allocations for the F1 and F2 frequencies for 'hard' and 'heard' were investigated for maps with 12 electrodes. These are shown in Table 14.

Table 14 Frequency Allocation for the vowel tokens 'hard' and 'heard'

Map	Electrode that F1 is assigned to for 'hard'	Electrode that F2 is assigned to for 'hard'	Electrode that F1 is assigned to for 'heard'	Electrode that F2 is assigned to for 'heard'
Default	5	6	4	7
L0U0	5	6	4	7
L0U1	5	6	4	7
L0U2	5	7	4	8
L1U0	5	6	4	7
L1U1	5	7	4	8
L1U2	6	7	5	8
L2U0	5	7	5	7
L2U1	6	7	5	8
L2U2	6	8	5	8

For all the maps except for L2U1 and L2U2, 'hard' was confused only with 'heard'. 'Heard' has separated F1 and F2, as shown in

Figure 84 but these formants activate a similar area of the cochlea to the F1 and F2 of 'hard'. It may be that when the token 'heard' is presented, CI users are confident that this is 'heard' due to the separated vowel formants. When 'hard' is presented, CI users are able to identify that a similar area of the cochlea is being excited but are uncertain as to the spacing of the formants and sometimes imagine that the spacing of the formants is greater than it actually is.

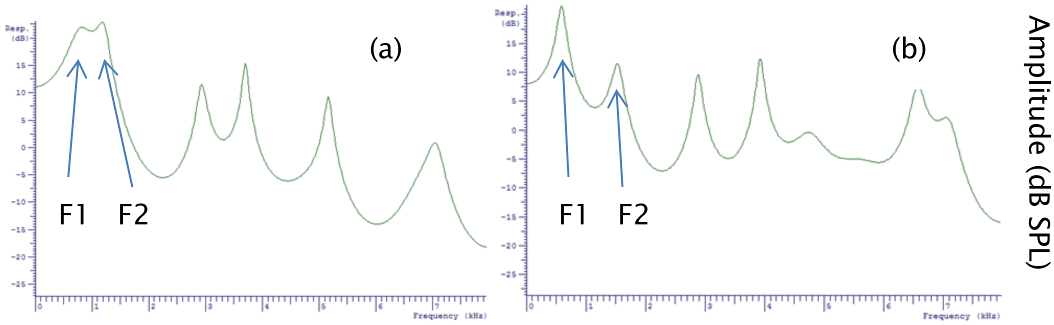


Figure 84 Vowel formants for (a) 'hard' and (b) 'heard'. Notice the separated F1 and F2 for 'heard'

Vowel confusions were also analysed for P1, who was an outlier with lower scores for the vowel test, when compared with the other participants with above chance scores for basal electrodes on the PCT. Vowel confusions for P1 are shown in Table 15.

Table 15 Vowel confusions shown as percent correct for P1: presented tokens are shown in the first column and perceived tokens are shown in the first row. Orange shaded boxes pertain to the correct answer.

totals	had	heard	hard	heed	hood	who'd	Hid	Head
had	98	0	2	0	0	0	0	0
heard	0	84	10	0	0	2	0	4
hard	0	42	58	0	0	0	0	0
heed	0	0	0	100	0	0	0	0
hood	0	0	0	0	2	0	94	4
who'd	0	0	0	98	0	2	0	0
hid	0	0	0	0	2	0	98	0
head	2	2	4	2	0	0	4	86

It was found that P1 confused ‘who’d’ and ‘heed’, and ‘hood’ and ‘hid’ in addition to ‘hard’ and ‘heard’. ‘Who’d’ was more often perceived as ‘heed’ and ‘hood’ was more often perceived as ‘hid’. ‘Heed’ has similar F1 but higher F2 than ‘who’d’;

'hid' has similar F1 but higher F2 than 'hood'. The persistent errors suggest that the F1 cue has been identified approximately correctly but the F2 cue has been either ignored or perceived as higher than it is. A possible explanation is that F1 is dominant for this participant and possibly that F2 is too quiet. At the end of the study, P1 was invited back to the clinic for further tuning, using objective measures (electrical stapedial reflex thresholds) and it was found that the apical electrodes had higher comfort levels relative to the reflex thresholds when compared to the middle and basal electrodes.

5.4.3 Music Perception

Adjustment of both the upper and lower frequency boundaries affected the rating of natural sound quality, as shown in Figure 72 and Figure 73. Additionally, the rating was correlated with the amount of frequency shift of the map, when compared to the L0U0 condition, (Figure 74 [R^2=0.77]). This suggests that the perceived pitch accounted for a large part of the variance in relation to the natural sound quality rating.

For the upper frequency boundary, basal shift was accompanied by a reduction in the frequency range, whereas for the lower frequency boundary, basal shift was accompanied by an increase in the frequency range. The results for natural sound quality rating indicate that participants were unconcerned about the loss of frequency range at the apical end for the L0 maps: L0U0 was rated as having similar naturalness to the default map, even though sounds from 100 to 224 Hz were not included in the map. The lowest notes in the song (F3 to A3) had F0 less than 225 Hz, and would have been attenuated by the L0 maps. It maybe that the lower notes within the song did not greatly influence the naturalness rating but there is also the possibility that the rating of naturalness was not dependent on F0.

It is likely that participants' attention would have been drawn to the channels with the highest amplitudes when listening to the song. Spectral analysis of individual notes, as shown in Figure 54, shows that the higher harmonics had greater amplitude than F0, by as much as 20 dB. The third octave bands with the highest amplitudes had centre frequencies of 630, 1000, 1250 and 2500 Hz for the note E3 (330 Hz), corresponding to the second, third, fourth and eighth harmonics.

Participants rated the L2 maps as less natural than the L0 maps. This suggests that electrodes four to six were more influential in the rating than electrodes one to three, as the default frequency allocation is closer to the L0 maps for electrodes four to six, corresponding to frequencies of 500 Hz to 1000 Hz approximately, and closer to the L2 maps for electrodes one to three, corresponding to frequencies less than 500 Hz approximately. This is consistent with the spectral analysis above, suggesting that the mid frequencies were more important than the low frequency F0, for rating naturalness for this song.

5.4.3.1 Participants' abilities to perform pitch-related tasks

Nine out of the twelve participants who attempted the experiment were able to perform both of the pitch-related assessments and eleven of them were able to perform one of the assessments. P6, who was unable to perform either assessment, had difficulty with the PCT for approximately half of the electrode pairs tested. This suggests that these tasks may require a minimum level of frequency discrimination ability. P12 had difficulty with the pitch rating task: she described the maps with the greatest basal shift as being low pitched rather than high pitched. Similarly, P3 appeared to have difficulty with pitch direction when she attempted the pitch adjustment task in her first session. For three maps, for which she had correctly identified as sounding high pitched for the pitch rating, she adjusted the pitch upwards rather than downwards. P3 realised that she found this task difficult and commented that a person with more musical training might find it easier. However, the correlation between the frequency shift in the map and the pitch adjustment was extremely high for the remainder of the group (R^2=0.94). This was greater than for the correlation between frequency shift and pitch rating (R^2=0.85) and had the additional benefit that the perceived amount of frequency shift could be measured. This was achieved in spite of the fact that the majority of participants had limited or no music training and three of them were not previously familiar with the song.

5.4.3.2 Perception of the pitch of the song with the default map

The default map was rated as having close to correct pitch, on average, by the group. The average pitch adjustment was less than one semitone (71 cents), in the downwards direction. This suggests that the majority of participants have acclimatised to their CIs. Had the Greenwood map been appropriate for experienced CI users, or even the SG map described by Stakhovskaya *et al.* (2007), it is likely that participants would have made much larger adjustments to the pitch of the song in order to correct the pitch of the default map. Insertion angles for P1, P11, P12 and P13 were estimated from post-operative X-rays for experiment 1 and were found to be between 570 and 680°, consistent with insertion angle measurements for the MED-EL standard electrode array reported elsewhere Radeloff *et al.* (2008). In order to map their cochlear implants to the Greenwood function, large apical shifts were required (0.5 to 0.9 octaves on electrode 6). Even larger apical shifts may have been required to map the frequency allocation to the Greenwood function for some of the other participants in this experiment, as they had shorter electrode arrays (Flex28), which give shallower insertion angles on average. It is highly unlikely that the participants in this experiment would perceive the Greenwood map as having normal pitch, as they rated the default map as sounding correct, even though it is shifted in the basal direction by half an octave or more from the Greenwood map. The findings from this experiment are more consistent with the findings of Plant *et al.* (2014), suggesting acclimatisation to the implant's frequency allocation or to the pitch of the most apical electrode in the majority of cases.

5.4.3.3 Perception of the pitch of the song with the alternative maps

For the alternative maps with basal shift, the place-pitch cue would have produced a high-pitch sensation whilst any temporal pitch cues would have suggested that the pitch was unchanged, as the song was presented at the same pitch each time participants were asked to rate the naturalness and pitch of the song. A conflict between the place-pitch and temporal pitch cues would have been present for the maps with basal shift. When the pitch of the song was adjusted using the slider, this discrepancy would have been maintained at the same level. The majority of participants were able to rate the pitch in line with the place-pitch cue and make the pitch adjustment, in spite of this potential confusion.

5.4.3.4 Pitch adjustment

The correlation between the frequency shift in the map and the mean pitch adjustment is remarkably high over the group (r=0.968). However, the gradient of the regression line is -0.74, indicating that participants adjusted the pitch of the song by a smaller amount than the frequency shift in the map. This finding is consistent with the frequency compression reported in pitch matching studies (Baumann *et al.*, 2011, Boëx *et al.*, 2006, Zeng *et al.*, 2014, Plant *et al.*, 2014). The amount of compression was found to vary between individuals: only P1 had the expected one-to-one relationship between frequency shift and pitch adjustment of the song. For the remaining nine participants who were able to manage the pitch adjustment task, the regression line had a slope between -0.48 and -0.8. This suggests that expansion of the frequency allocation could be helpful, assuming that the corresponding reduction in frequency range is not large enough to have a negative impact on the sound quality. However, this should be implemented at the time of fitting, ideally, given the fact that acclimatisation to the new allocation would need to take place. Another potential method of reducing frequency compression is deeper insertion of the electrode array.

5.4.3.5 Implications for mapping

The majority of participants in this study were able to make an adjustment to the pitch of a song appropriately, in response to a change of frequency allocation. The adjustment took only a short amount of time and required only a computer and soundfield or Otocube system. Assessments of this nature could be helpful for tuning cochlear implants, in that they represent everyday sounds, and allow aspects of sound perception to be investigated, which are often overlooked in traditional tuning methods. In particular, this technique could be used to identify individuals who had not completely acclimatised to their existing frequency allocation. This technique could also be helpful for identifying CI recipients with frequency compression and expansion of the frequency allocation could be applied in an attempt to compensate for this.

Chapter 6: General Discussion

This study has investigated the potential advantages and disadvantages of assigning CI frequency allocations for individual recipients using different approaches. The devices which were investigated in this study were all manufactured by MED-EL, who recommend that the default frequency allocation should be used unless there is a strong reason not to do so (Durst, 2015). Within the group of CI recipients who participated in experiment 1, a wide range of insertion angles were found. This was expected, given the wide variations in cochlea size and shape and insertion depths which are reported in the literature (see section 2.3.1 for further details). As a result, frequencies were allocated to different insertion depths for individual participants with the default map. Their implants were suitable for frequency allocation investigations, as they all had long electrode arrays and flexible filters.

The default frequency allocation for MED-EL implants spreads out speech frequencies across all available electrodes using a fourth order polynomial function. The frequency range is broad (100 Hz to 8500 Hz), with the intention of transmitting the whole speech frequency range from low frequency F0 cues right through to children's higher-frequency phonemes. This approach makes an implicit assumption that the optimum frequency allocation is the same for (almost) all CI users. This study tested this assumption and found that it did not hold true for the group of CI users included in this study, who had a range of insertion depths and varied pitch perception abilities along the electrode array. This implies that frequency allocation will need to be adjusted for individual CI users in order to optimise performance.

Three alternative approaches to setting the frequency allocation were investigated. The first two alternatives mapped frequencies to fixed positions in the cochlea. In one of these, frequencies were mapped to the anticipated position of maximum excitation of the basilar membrane in normal cochleae, corresponding to the normal frequency-to-place map for acoustic stimuli and given by the Greenwood function. The other involved mapping frequencies to a reduced area of the cochlea, covering approximately 95% of the length of the SG and which may represent a closer match to the perceived pitch at electrodes than is represented by the Greenwood function. The third approach was a pitch-perception based approach. The first map to be trialled for this approach had reduced bandwidth assigned to the apical electrodes and some basal shift, with the intention of improving pitch perception for participants with poor electrode discrimination for apical electrodes. The pitch-perception based approach was developed further in experiment two and is the main outcome of this study.

Whilst data relating to frequency allocation is the main contribution to the scientific literature from this study, there were also aspects of the methodology which were novel and will be discussed here.

6.1 Novel Developments in Psycho-acoustic testing

6.1.1 Multiple Testing of Frequency Allocations

In the experiments conducted for this study, participants were all high-performing CI users and the results of the study suggested that they had successfully acclimatised to the processor's default frequency allocation. In the literature there are reports of incomplete acclimatisation for some CI recipients (see section 2.9). If there is a concern that an individual may be struggling to acclimatise to their CI, it would be desirable to be able to assess if their map is 'pitch-matched' to their memory of acoustic hearing. This could be facilitated using the technique employed in experiment 2 of this study with the IMAP. Different frequency allocations could be rated for their perceived pitch and this could be verified by asking the implant recipient to adjust the pitch of a song to the 'correct' pitch using the pitch slider. This would only need to take a few minutes if the clinician guided the process. It would also be an opportunity to assess frequency compression.

6.1.2 Electrode Discrimination and PCT

The electrode discrimination test used in experiment 1 proved to be valuable and was not unduly onerous for CI users. The test was limited in so far as it only tested discrimination ability and there were ceiling effects, but significant differences in discrimination between electrode pairs were still found, without the need to stimulate the implant directly using custom software. The test was presented via headphones, which is unusual for clinical testing with CI users, as most testing is done in soundfield. Soundfield presentation was not an option for this test, due to the stimuli being pure tones, which would have produced standing waves. Circumaural headphones were used so that they would fit comfortably over the processor. No problems were encountered with their use and calibration was achieved by the use of a custom lead from the processor to the line-in of a computer. The use of headphones could be considered for testing CI users more generally.

The PCT used in experiment 2 was presented via Otocube, which is essentially a speaker in a sound-treated box, with a microphone at a test spot, to check sound levels. Presentation of stimuli via Otocube was very convenient as it was suitable for the PCT, music assessments and speech perception tests. It also enabled the tester to be present in the same room as the participant for the speech tests. Again, useful information was ascertained without the need for custom software to stimulate the implant directly. The maps used in the test were activated in the normal clinical software.

The PCT was reconfigured for this study, to enable the pitch percept associated with adjacent electrodes to be compared, and it proved to be more satisfactory than the electrode discrimination test used in experiment 1. Testing pitch contour yielded additional information related to the change of pitch direction, which was not available from the electrode discrimination test. The PCT did not test resolution, which would have been yet more desirable, but the contour results were sufficient for identifying electrode pairs offering poor pitch perception. The greater number of trials meant that the results could be interpreted with more confidence than those from the electrode discrimination test. However, the full test took some considerable time (in the region of an hour for all electrode pairs), which would be difficult to justify in a busy CI clinic and quite onerous for CI recipients. It would be desirable to reduce the testing time by reducing the number of pairs tested or by reducing the number of trials, if this could be done without compromising the results.

The PCT identified an issue with pitch perception for P2, which warrants further investigation. This issue had not been identified through routine tuning. Pitch perception was poor at the basal end of the array. Clinical data from P2 showed that electrical impedances had increased over time for the same electrodes and comfort levels were higher when compared with apical electrodes. This combination of findings could be explained by extrusion of the electrode array. Dietz *et al.* (2015) has found that migration of flexible arrays is possible and is typically accompanied by increases in basal electrode impedances. Such an occurrence would be likely to be accompanied by a loss of electrode discrimination for the affected electrodes. It is possible that the PCT could help to identify significant clinical issues such as migration of electrode arrays.

The PCT results suggest that pitch perception testing could be helpful in routine clinical practice, beyond adjustment of the frequency allocation. The PCT proved to be feasible for use with the adult CI users who participated in this project and could be used for this purpose.

6.1.3 Vowel test

The vowel test proved to be easy to administer, taking approximately five minutes or less per test and was acceptable for participants, being less onerous than the sentence test. This test also offered novel information which had not been found in routine clinical practice. In addition to showing an effect of basal shift, the test was able to identify vowel confusions for P1 in experiment 2, which had not been found from routine clinical work and for which there is a potential explanation, meaning that the problem could be resolvable. The vowel test also picked up a general confusion of ‘hard’ for ‘heard’. This suggests that pitch perception is imprecise for the formant frequencies of ‘hard’ and this is an area for future work.

The vowel test allows low and higher frequency components of speech to be considered separately. The results for the vowel test in experiment 2 indicate that both F1 and F2 information is important for CI users: shifting of both lower and higher frequency sounds had an impact on performance in the test. This is consistent with the findings of Whitmal and Deroy (2012), Fourakis *et al.* (2007) and Henry *et al.* (2000). Use of the vowel test in clinical practice could help to ensure that discrimination is good for sounds of different frequency.

There are some things which could be improved for test. For example, if the test were able to derive a vowel confusion matrix for each test and show this at the end of the run. Another improvement would be find critical differences for this test, so that it would be easy to determine if two scores were significantly different or not.

6.2 Optimisation of Frequency Allocation

6.2.1 Frequency Mapping to Fixed Positions in the Cochlea

In the first experiment, frequencies were allocated to fixed positions in the cochlea, using insertion angles estimated from post-operative X-rays.

Two alternative frequency maps with frequencies assigned to given positions in the cochlea were investigated: the first was calculated from the Greenwood function

(Greenwood, 1990). The potential advantage of using this function is that it approximates the frequency map of the normal cochlea and may be perceived as sounding natural. Possible disadvantages of using the Greenwood function include the fact that electrodes might not be available in the appropriate positions to allow the whole speech frequency range to be mapped and that frequencies may be assigned to the apical end of the cochlea, even beyond the SG, where pitch perception may be less acute. A further disadvantage is that the implant's filters may not be able to manage to match the desired frequency allocation at the extreme ends of the array, if the desired bandwidth for an end electrode is smaller than for the other electrodes.

For the second fixed-position frequency map, the Greenwood function was calculated as a function of SG length. The potential advantage of mapping sounds to this area is that potentially pitch perception will be good for the whole speech frequency range. It may also be closer to a frequency matched map for some individuals, as pitch matching studies have shown pitch matches significantly below the Greenwood function for some individuals. However, this map also has the potential disadvantages of the Greenwood map, in that the CI electrodes may not necessarily be in the desired positions, and that programming the map may result in loss of frequency range and/or deactivation of electrodes and difficulties with accommodating a more limited bandwidth at the extreme ends of the array.

The results of the first experiment indicated that the potential advantages of the fixed position maps did not outweigh the disadvantages, especially for the Greenwood map. Both alternative maps resulted in electrodes being deactivated (eighteen for the Greenwood map and twenty for the SG map in total for the ten participants) and the Greenwood map resulted in a substantial loss of frequency range for those with shallower insertions. Participants experienced frequency shift from their clinical maps: for the Greenwood map this was apical shift (resulting in a lower pitch percept than for the clinical map) ranging from 0.5 to 1.4 octaves for electrodes four to nine (mean = 0.9 octaves), whilst for the SG map most participants experienced basal shift over a large part of the electrode array (resulting in a higher pitch percept) with shift averaged over electrodes four to nine from 0.1 to 1.0 octaves (mean = 0.5 octaves). Performance was negatively correlated with the amount of shift away from the clinical map. Whilst some loss of performance may be attributed to the loss of frequency range and electrodes, even those with limited loss of frequency range performed poorly with the Greenwood map and rated it as having poor sound quality in comparison with the clinical map. If the Greenwood map represents a natural pitch-matched map for this group of individuals, an improvement rather than a decrement in speech perception would be anticipated. The fact that a large decrement was found shows that the potential advantage of the Greenwood map was not realised.

The music rating results from experiment 2 offered evidence that participants perceive the default map as having close to normal pitch. This suggests that they have acclimatised to the implant stimulation and will no longer perceive the Greenwood map as sounding natural. This finding is consistent with the results from experiment one. Some published studies offer evidence of acclimatisation to the implant's frequency allocation (e.g. (Reiss *et al.*, 2007, Fu and Shannon, 2002 Harnsberger *et al.*, 2001). The results from this study are consistent with studies showing acclimatisation, rather than the limited number of pitch matching experiments which suggest that the Greenwood function represents the frequency-position function for CI recipients, even after acclimatisation has occurred (Vermeire *et al.*, 2008, Carlyon *et al.*, 2010). It should be remembered that this study was performed with unilaterally implanted CI recipients who were profoundly deaf in both ears, whereas the pitch-matching studies reported in the literature were performed with unilaterally implanted CI recipients who had normal or near-normal hearing in their contralateral ear. The participants in the Vermeire *et al.* study also had relatively deep insertions.

The SG map resulted in poorer performance for the group than the clinical map, but not for all participants, and two participants who experienced only a limited amount of shift with this map preferred it to their clinical maps and continued to use it at the end of the study. It may be that in these cases the logarithmic frequency spacing of the map or the minor reduction in frequency range at the apical end or the deactivation of the most basal electrode was perceived as an improvement.

For the remaining participants, the SG map was not perceived as an improvement or was perceived as worse than the clinical map.

This study only investigated two fixed-position maps. Another fixed-position frequency map has been proposed in the published literature: the SG matched map by Stakhovskaya *et al.* (2007). This map is similar to the Greenwood map for most of the basal turn but frequencies drop more quickly with insertion angle around the 360˚ point and also in the middle turn.

Figure 85 shows this map for comparison. If the Stakhovskaya Greenwood and SG functions had been tested in this study instead of the Greenwood map which was implemented, the frequency shift at some points would have been less (between 0.02 and 0.21 octaves less for the Stakhovskaya Greenwood map and between 0.12 and 0.44 octaves less for the Stakhovskaya SG map), so it is possible that results with these maps would have been somewhat better than those for the Greenwood map which was tested. However, there would still have been a similar loss of frequency range at the apical end for those with shallow insertions, even with the Stahkovskaya SG map.

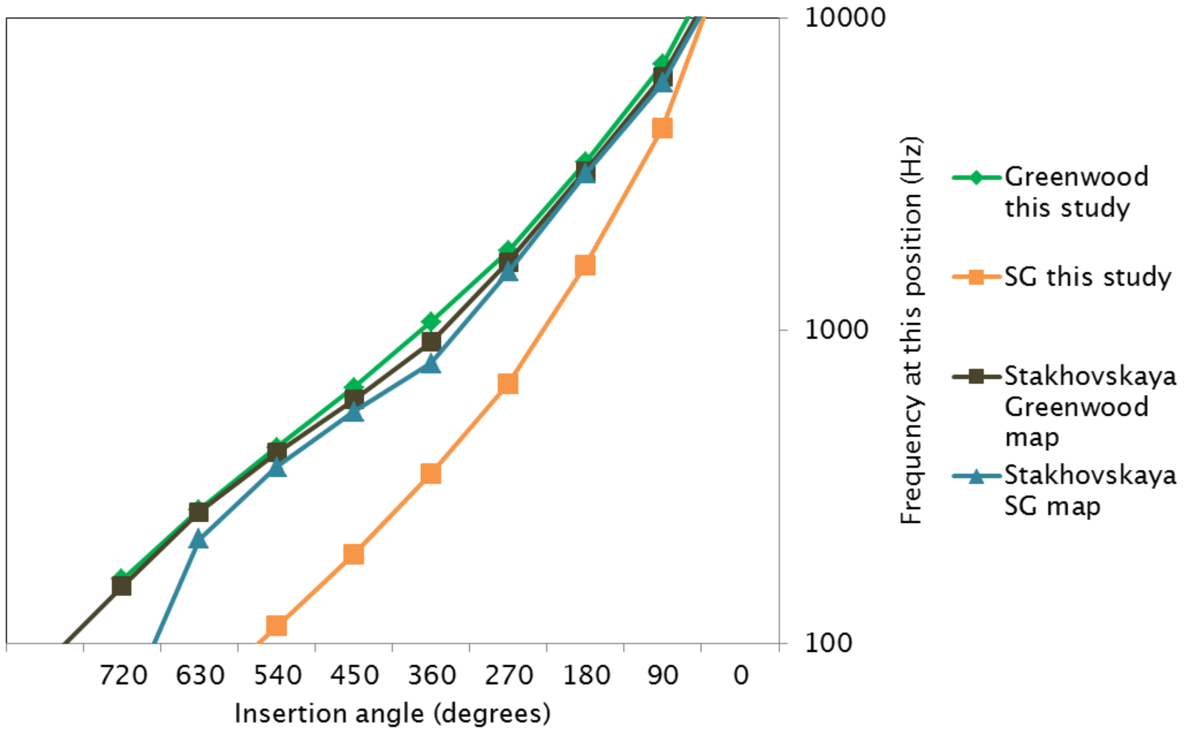


Figure 85 Stakhovskaya matched maps compared with the Greenwood and SG maps in this study

Participants experienced both frequency shift and loss of frequency range with the Greenwood map. As they co-varied, it is not possible to ascertain how much of the poor performance can be attributed to the effect of each one. However, as noted above, even those with limited loss of frequency range performed poorly with this map. Additionally, frequency shift was associated with poorer performance with the SG map, in the absence of loss of frequency range. Figure 86 shows the effect of frequency shift on BKB sentence scores, whilst Figure 87 shows the effect of lower frequency boundary on BKB sentence scores. It might have been possible to separate the effects of these two variables if the participants with deeper insertions had also been tested with maps with loss of frequency range in addition to the apical shift associated with the Greenwood function.

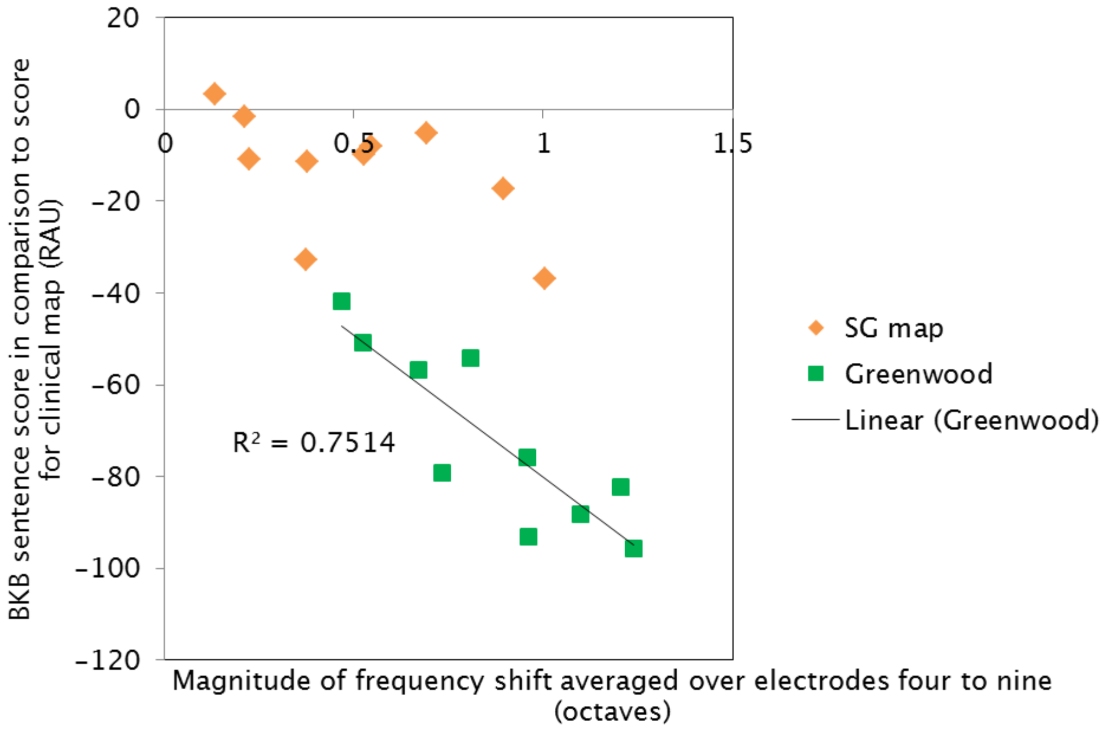


Figure 86 BKB sentence scores as a function of frequency shift from the clinical map

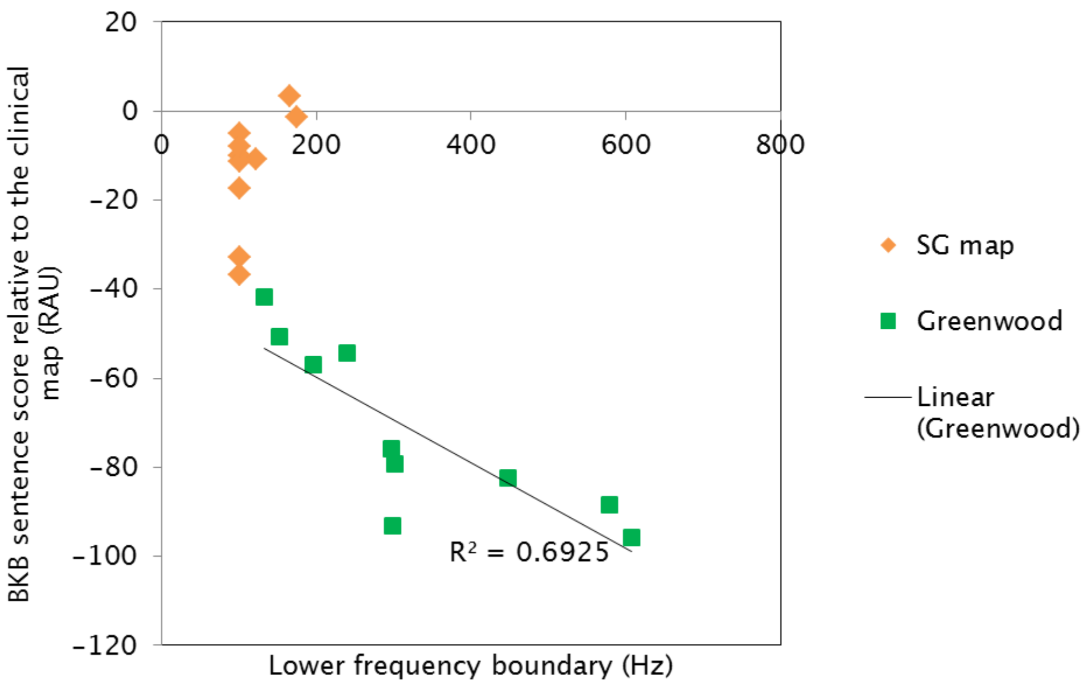


Figure 87 BKB sentence scores as a function of lower frequency boundary

It is interesting to compare the results of this study with those from Başkent and Shannon (2005), who investigated the effects of frequency shift and loss of frequency range separately, when they investigated the effect of insertion depth on speech perception in a group of MED-EL CI users. They found that a substantial amount of frequency range could be sacrificed (up to approximately 1 kHz), before a compressed map gave better results than a 'matched' map, in an acute study. Başkent and Shannon found that acute frequency shifts of more than one octave at the apical end of the array can be highly detrimental to speech perception, whereas a loss of low frequencies can have a more limited effect up to approximately 800 Hz. In experiment 1, the frequency shifts for the Greenwood map extended over the whole electrode array and exceeded one octave in some cases. By comparison, the lower frequency boundaries ranged from 133 to 608 Hz. Based on the results from Başkent and Shannon's study, and the correlation between frequency shift and poor performance with the SG map in this study, the frequency shift may have had a greater effect than the loss of low frequencies.

However, there is also evidence in the literature that low frequency information is important for CI users for speech perception and is influenced by frequency allocation. Whitmal *et al.* (2015) found that frequency importance functions for vowel-consonant-vowel tokens were different for vocoded compared to normal stimuli, with increased importance for lower frequencies with vocoded speech. Fourakis *et al.* (2007) found that assigning more filters to frequencies below 1 kHz could improve transmission of F1 information in vowel perception tasks. Henry *et al.* found that the removal of high frequencies (above 2600 Hz) from a CI map had less effect on word recognition than the removal of either low or mid frequency sounds.

Given the fact that the electrodes of a CI are fixed in position once surgery has taken place, it is difficult to envisage a situation in which a fixed-position frequency map will result in optimum performance for all CI users. There are several reasons for this. The first reason why a fixed-position map is unlikely to be optimal for all CI users is that the position of individual electrodes varies considerably between individual recipients: fixed-position maps result in adjustment of the frequency range, deactivation of electrodes and some differences in frequency bandwidths. This makes matching a frequency allocation to fixed positions in the cochlea difficult from a practical point of view.

The second reason why a fixed frequency-to-position map is unlikely to be optimal for all CI users is that pitch perception varies with insertion angle but not in the same manner for all CI users (this issue is discussed further in section 6.4). Difficulties with pitch perception were found at both ends of the electrode array in experiment 2 but varied considerably between CI recipients. This means that a fixed frequency-to-position map would result in better pitch perception for some frequencies for some CI users than others.

Nevertheless, it is possible to imagine an improvement to the fixed frequency-to-position maps which were trialled in experiment one of this study. The improvement would involve activating all the available electrodes at the basal end of the array, which were not beyond the end of the OC, allowing the frequency allocation to be spread over a larger area.

A third reason why fixed-position frequency maps are unlikely to be optimal for CI users is that ‘pitch-matched’ maps also vary for CI recipients. If a pitch-matched map was represented by the Greenwood function for CI users, performance with the Greenwood map should have been better. One possibility is that variations in cochlear shape and size between individuals meant that the Greenwood map was not a good representation of a ‘matched’ map for participants in the study. However, the results of experiment 1 part 1 and the IMAP results from experiment 2 do not suggest that this is the case: rather, they suggest that CI users have acclimatised to their processor’s frequency allocation and this now represents a ‘pitch-matched’ map for them. If fixed-position frequency maps do not represent ‘matched’ maps for CI users, the potential benefit of them is not realised and other issues (such as ensuring a sufficiently large frequency range and allocating important sounds to areas of good pitch perception) must be considered to be of greater importance.

There is a substantial amount of evidence of acclimatisation for CI users in the literature (see section 2.9); acclimatisation is possible if the individual’s memory of acoustic pitch is not too far removed from what is presented by the implant and the individual is cognitively able to make the adjustment (McKay and Henshall, 2002, Eisner *et al.*, 2010). In the case of participants in this study, who were using MED-EL standard and FLEX28 electrode arrays, there is evidence that acclimatisation had occurred, so it should be considered that the implants’ frequency allocations were not too far removed from individuals’ memories of acoustic pitch. The same applies to the maps which offered improved performance over the default map in experiment 2. There may be some short-term benefits from matching the frequency allocation to the individual’s memory of acoustic pitch (Svirsky *et al.*, 2015), but this should not be the over-riding consideration, as ongoing benefits are more important. Svirsky *et al.* recommend gradually working towards the target map from a more matched map, as this makes acclimatisation easier. The pitch adjustment task used with the IMAP in experiment 2 offers a potential way to make this happen: an approximately 'matched' map could be identified from a selection of different allocations and if the 'matched' map was less than ideal for other reasons (such as limited frequency range), progressive maps towards the target map could be offered.

6.2.2 Relationship between Electrode Position and Perception

The current situation across all CI users and devices is such that both insertion angles and pitch perception vary widely but these things are not related to each other. This is far from ideal, as a CI user with poor pitch perception in the middle turn may have a deep insertion and be using electrodes which cannot be discriminated from each other, whilst a CI user with the potential for good pitch perception in the middle turn may have a shallow insertion with no available electrodes in this area. It is also possible for a CI recipient with poor pitch perception near the base of the cochlea to have electrodes very close to the round window.

Even though fixed-position frequency maps are unlikely to offer best performance for CI recipients, it would still be helpful to find the optimal area of the cochlea (on average) for electrical stimulation for those with normal anatomy. The fact that electrode arrays vary so widely in length and design between different manufacturers suggests that this has not yet been achieved, although a large amount of work has been done which can contribute evidence towards this goal. Knowledge of the optimal area for stimulation would help with the design of future electrode arrays, or with selection of the best choice of array from those which are currently available. One possible approach for electrode length selection has been suggested by some researchers (Hochmair *et al.*, 2015), and this involves determining the desired length of the electrode array from the size of the cochlea. Such an approach also requires surgical techniques which will result in consistent placement of electrodes. If more consistent insertion depths could be achieved without trauma to the delicate cochlear structures, there would be less variability in pitch perception between different electrodes between individual CI recipients. If the depth of insertion was optimised, it is also likely that performance would be improved for some individuals. In such a scenario, the use of a default frequency allocation would be more appropriate.

It could be argued that rather than trying to determine the optimal area of the cochlea for stimulation, it would be easier or more effective simply to limit the insertion depth to the area of the cochlea which is likely to offer good pitch perception for nearly all CI users (such as the basal turn or a little more than that) and to use a default frequency allocation. However, this study shows that there is a potential drawback to this approach. If the area of the cochlea which is stimulated by the implant is restricted, this results in frequency compression. The musical pitch adjustment results from experiment two suggest that the majority of CI users who took part in the experiment experienced some degree of frequency compression, even with relatively long electrode arrays. This is consistent with the findings of Zeng *et al.* (2014) and Plant *et al.* (2014). It would be undesirable to compress the frequency range of the implant further by limiting the insertion depth of the implant, as this would be likely to increase the amount of frequency compression which they experienced. The results of a large study by Holden *et al.* (2013) also appear to be consistent with this idea. In their study it was found that participants with scala tympani insertions and greater angular distances between their apical and basal electrode arrays performed slightly better on word perception tests than those with scala tympani insertions but smaller angular distances.

In order to ascertain the optimal area of the cochlea for stimulation, there is a need for greater certainty with regard to the relationship between electrode position and perception of pitch, loudness and comfort for individual electrodes, alongside performance with the device. Pitch matching studies offer some pitch-related data towards this goal and this study adds some further data to that pool of information, as electrode discrimination was measured as a function of insertion angle in experiment 1 (see section 3.2.7). Electrode discrimination was found to be poorer in the middle turn than in the basal turn, consistent with findings from pitch matching studies discussed in section 2.5.3. If insertion angles were measured for the participants in experiment 2, further data relating to pitch perception as a function of insertion angle (from the PCT) would be available. Some of these angles are known.

6.2.3 Frequency Mapping According to Pitch Perception Ability

The third approach to adjustment of frequency allocation, which was investigated in this study, was based on pitch perception in different areas of the cochlea. Firstly, a map with basal shift relative to the default map and limited bandwidth for apical electrodes was trialled (the RFR map), to reduce the impact of poorer pitch perception at the apical end, which was an issue for some participants. The improved performance shown with this map in experiment 1 part 2, by three participants, suggested that it would be worth investigating the relationship between pitch perception along the array and performance with different frequency allocation settings more thoroughly. A second experiment was performed which assessed pitch perception using the PCT alongside performance with ten different frequency allocations, including the default. This gave some positive outcomes, which was in contrast to the fixed-position maps included in experiment 1.

6.3 Proposed Clinical Protocol

The PCT proved to be predictive of performance with different frequency allocations, as an interaction between scores on the PCT for basal electrodes and performance on the BKB sentence test was found. Moreover, some allocations offered improved performance when compared with the default allocation for some CI users. These allocations did not prove to be detrimental on the other measures (i.e. the vowel test and ratings of musical sound quality), so a strategy for selecting frequency allocation according to PCT score was developed. The criteria for development of the strategy were:

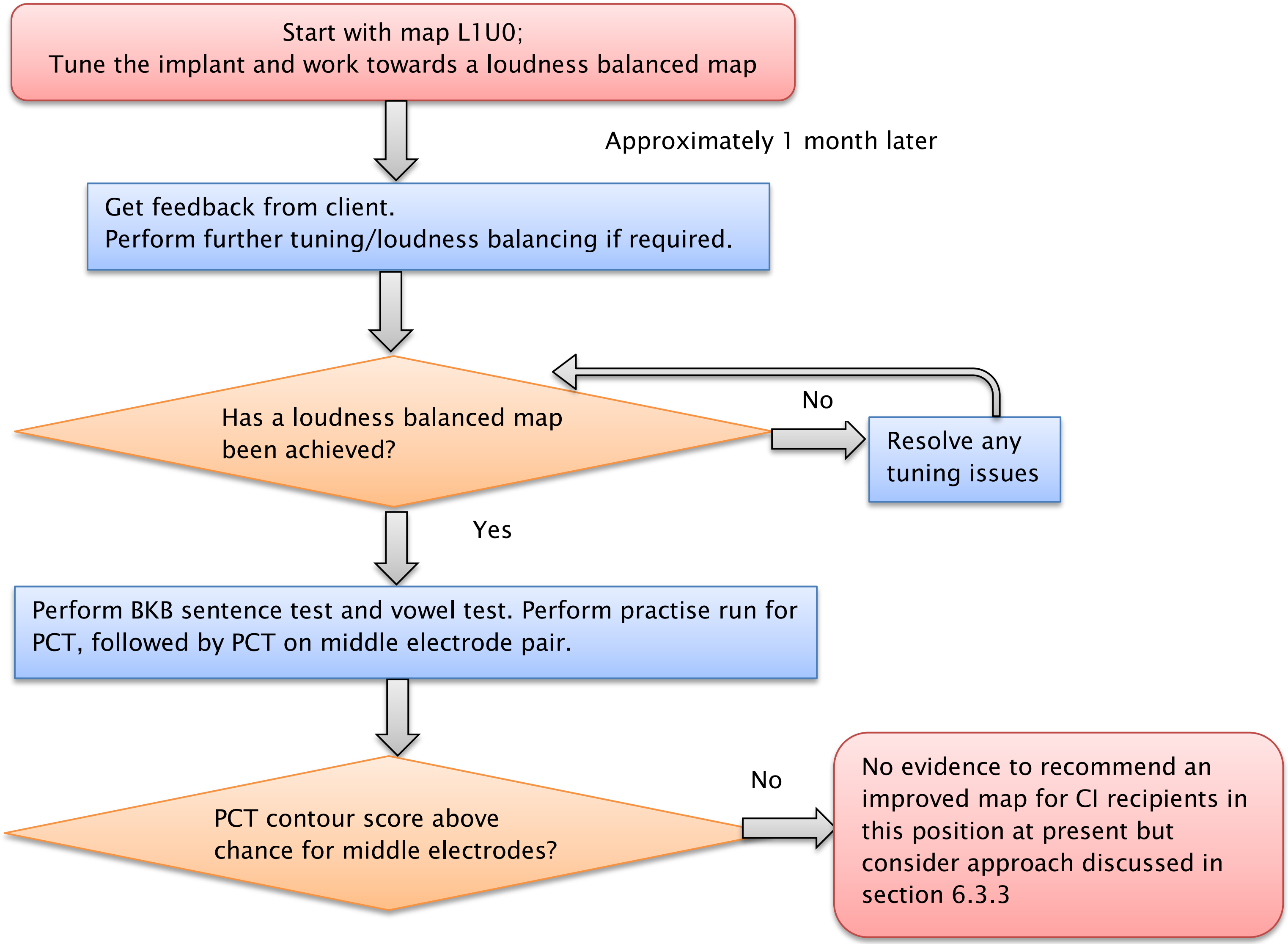
- The strategy is dependent on PCT scores. PCT scores for basal electrodes will be compared with those for middle electrodes and CI users will be assigned to groups 'good PCT scores for middle and basal electrodes', 'good PCT scores for middle electrodes but poor PCT scores for basal electrodes' or 'poor PCT scores for middle and basal electrodes'
- BKB sentence scores in noise will be considered for each of these groups and maps selected for the strategy will offer good performance
- The maximum number of maps will be limited to two for each group, to avoid participants having to trial lots of different maps
- No individual should be significantly disadvantaged when compared to the current situation, which is that they receive the default frequency allocation

The maps included in the strategy are the two maps which offered improved performance when compared to map L0U0 over the whole group and the default. Based on the group of participants tested within the study, the strategy offers immediate improvement in speech perception performance for some individuals, whilst not being disadvantageous to others. The development of the strategy is consistent with the hypothesis that the use of a default frequency allocation is not ideal for all CI recipients. It is also the most immediate and positive outcome of this study.

A summary of the strategy for selecting the frequency allocation is given in Table 16 and in more detail in Figure 88. As frequency allocation is not routinely adjusted for individual recipients at present, its introduction into CI clinics which follow manufacturers' recommendations would be novel.

Table 16   Strategy for selection of frequency allocation based on PCT scores

PCT for two most basal electrode pairs	Appropriate maps (choose the one with the highest score)
Above chance	L1U0 and L1U1
At or below chance for one or both pairs	L1U0 and default


Start with map L1U0;
Tune the implant and work towards a loudness balanced map
Approximately 1 month later
Get feedback from client.
Perform further tuning/loudness balancing if required.
Has a loudness balanced map been achieved?
No
Resolve any tuning issues
Yes
Perform BKB sentence test and vowel test. Perform practise run for PCT, followed by PCT on middle electrode pair.
PCT contour score above chance for middle electrodes?
No
No evidence to recommend an improved map for CI recipients in this position at present but consider approach discussed in section 6.3.3

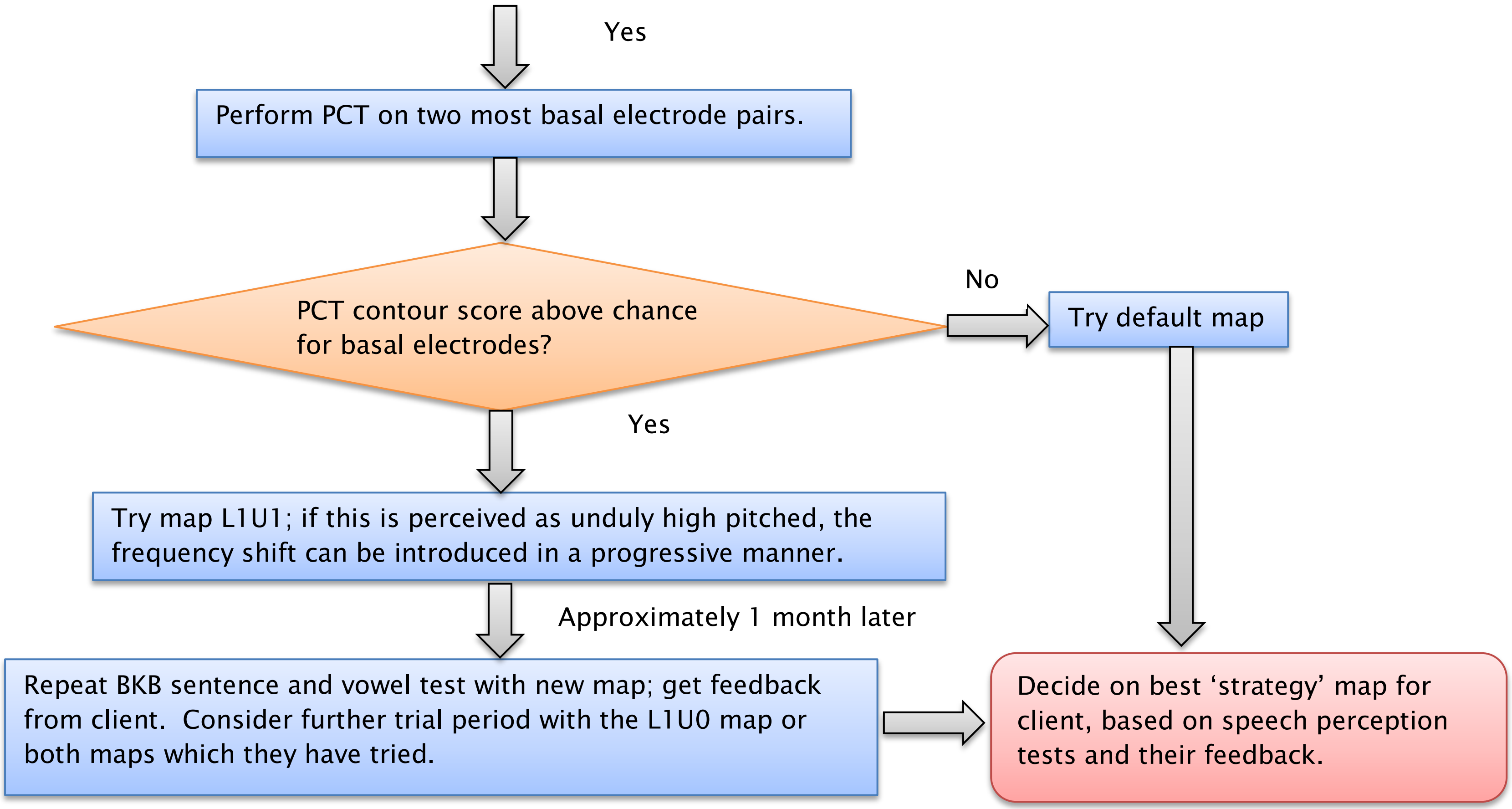


Figure 88 Flow chart of recommended frequency allocations for individual CI recipients

6.3.1 Choice of Maps for Individual Participants

BKB sentence scores are shown for the participants in experiment 2, with their scores for the default and new ‘strategy’ maps in Figure 89.

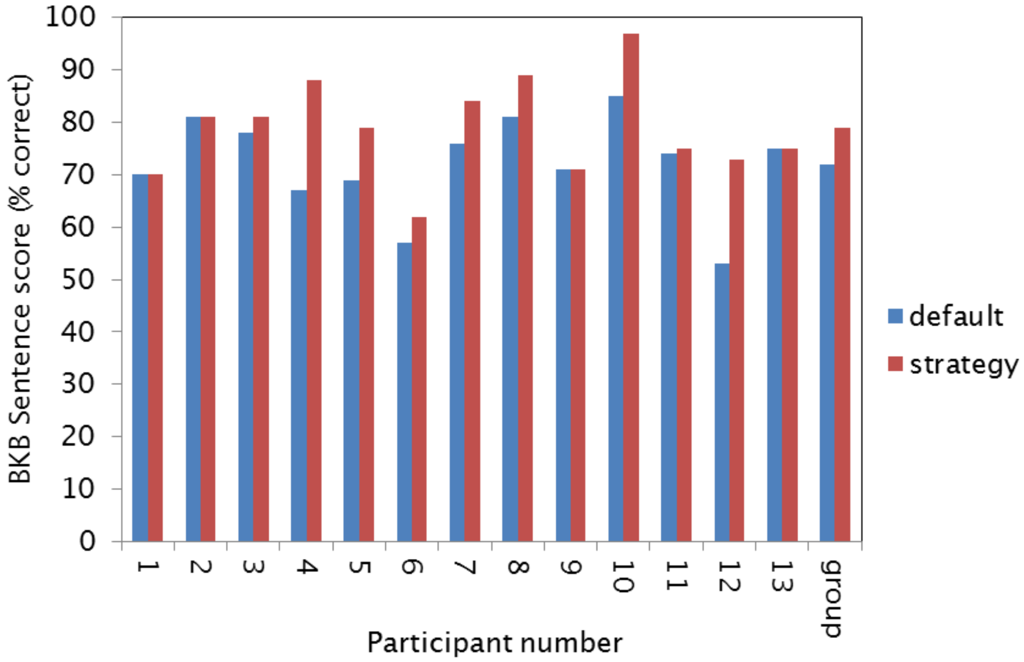


Figure 89 BKB sentence scores for the default map and for the 'strategy' map, which is either L1U0, L1U1 or the default

A paired *t*-test (2-tailed) was performed to analyse the effect of administering the strategy on the BKB sentence scores of this group of CI users. A significant improvement was found [$t(12)=-3.31$, $p=0.006$, $r=0.69$] for the strategy map as compared to the default, a large effect.

Results with the strategy map were also compared to the default map for the vowel test and for natural music quality. It was found from Wilcoxon’s signed ranks test that there was no significant difference in vowel identification performance for the default and strategy maps over the whole group [$Z=-1.46$, $p>0.05$]. Similarly, there was no difference in natural music sound quality rating, using a paired *t*-test (2 tailed) [$t(10)=-1.793$, $p=0.103$].

6.3.2 Next Clinical Steps

It would be advisable to test the new strategy with another group of CI users, to check that the findings are repeatable. This could be done with another group of experienced users. Participants in the study could be assessed with three different maps: the two strategy maps which are appropriate to them individually and the default map. Each map could be trialled for one month prior to being assessed with the same outcome measures that were used in experiment 2. For those who show benefit from the L1U1 map, the RFR map or L1U2 map could also be assessed to see if there might be further benefit from a larger shift once acclimatisation to a map with basal shift has occurred.

In addition, the PCT results suggest that a more comprehensive stratified approach to optimise tuning for pitch-related parameters would be desirable, especially for those with considerable variability of pitch perception along the array (e.g. P6 in experiment 2). This would include the selection of electrodes in addition to adjustment of the frequency allocation. Previous studies have found that deactivating electrodes in such cases can offer improved performance (e.g. (van Besouw and Grasmeder, 2011)). Future research work could address the need to look at both of these parameters concurrently, in order to optimise pitch perception for CI recipients in this position. An approach which may be suitable is suggested in 6.3.3.

6.3.3 Pitch perception based approach for selection of both frequency allocation and electrode selection

The PCT scores from experiment 2 of this study demonstrate the fact that there is currently considerable variability in the pitch perception abilities of a subset of CI users along the electrode array. For example, P6 only had above chance contour scores on the PCT for five out of eleven electrode pairs. This participant had been using her CI for approximately fifteen years but pitch perception difficulties not been noticed previously and so no action had been taken. The traditional clinical approach in cases where electrodes cannot be discriminated is to deactivate the electrodes in question, although this requires the problem to be identified first, which requires pitch perception to be tested. Pitch perception for CI recipients has not been routinely tested in the UK in the past, as far as the author is aware, as it is neither an obvious outcome measure (such as speech perception), or a measure which is incorporated into tuning procedures. In addition, there is no established method of pitch perception assessment which has come into general use.

Having said that, if P6’s poor pitch perception had been identified earlier, and the traditional clinical approach had been followed, this would have resulted in deactivation of approximately half of the electrodes. This is close to the limit where a reduced number of electrodes may limit performance, based on data from Wilson and Dorman (2008b). Deactivation of half of the electrodes would also require adaptation to a very different map. Deactivation of a smaller number of electrodes may be a better way forward, not just because it would be easier to acclimatise to but also as it would allow the most important speech frequencies to be allocated to the most salient area of the cochlea. This can be demonstrated when the band importance functions from the SII are considered alongside the PCT data for this participant. The band importance functions for speech are shown in Figure 90 alongside an adjusted function based on the data from (Whitmal and DeRoy, 2012). A smoothed trendline has been added, which is a cubic function. This function has been superimposed on the PCT data for P6 in Figure 91, and represents the BIFs for a map suggested by the author. The map has been devised with the intention of assigning the most important speech frequencies to the area where pitch perception is best. Only a limited bandwidth has been selected (approximately 170 to 5900 Hz) and logarithmic frequency spacing has been used. In addition, three electrodes have been deactivated: E10, E11 and E12. It would be a simple matter to calculate frequency maps in this way and to implement them in CI recipients' processors.

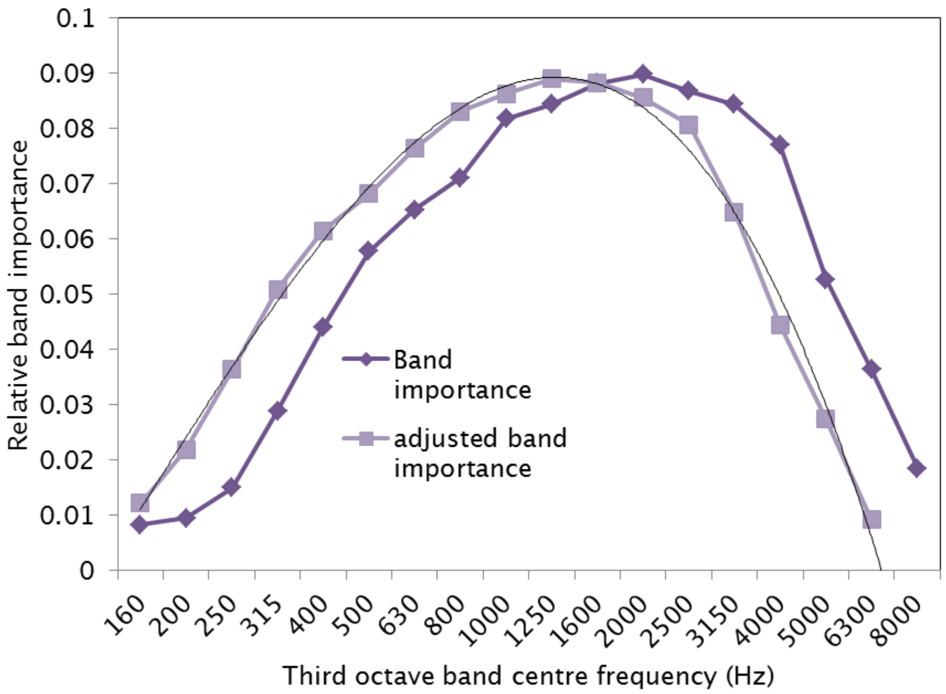


Figure 90 Band importance functions for speech intelligibility from the SII and the same transposed down half an octave.

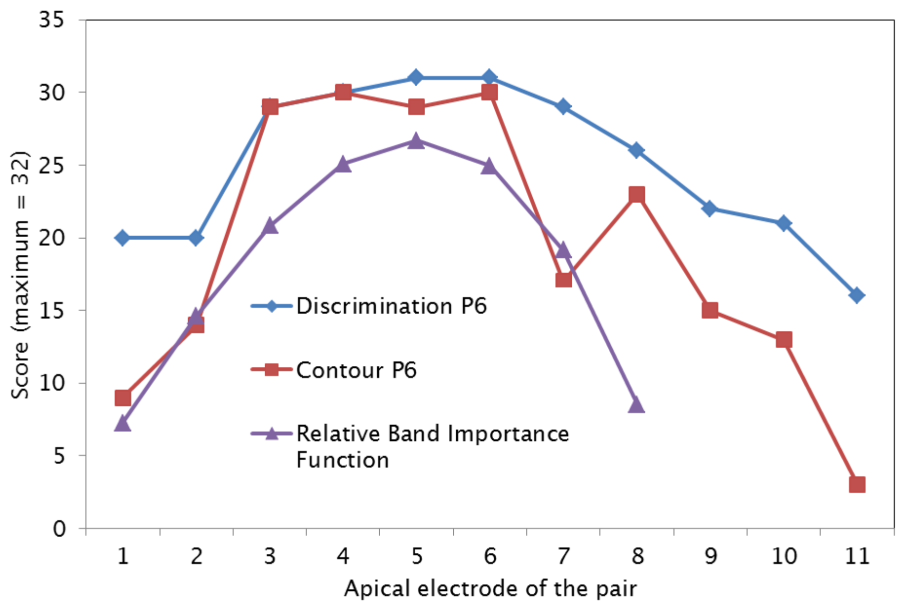


Figure 91 PCT scores for P6 and the relative band importance functions for a possible nine channel, logarithmically spaced map with a frequency range of approximately 170 to 5900 Hz suggested by the author.

6.4 Other Frequency Allocation Issues

6.4.1 Frequency Allocation Function Shape

The effectiveness of different shaped functions for CI frequency maps was only tested to a limited extent in this study. Logarithmic spacing of frequency bands offered comparable performance on speech perception measures to the default polynomial function, for maps with limited frequency shift, which were tested in experiment 2. For some participants with poor pitch perception at the apical end of the array, logarithmic spacing of the frequency range may have contributed to the improved BKB sentence scores in experiment 1 part 2. Additionally, the music ratings from experiment 2 suggest that some logarithmic maps offer a sound quality which is at least equivalent to that of the default map. This finding was in spite of the fact that participants were acclimatised to the default map.

Some pitch scaling, pitch sensitivity and pitch matching studies have shown largely uniform changes of pitch along the electrode array for individual CI users (Boyd, 2011, Nelson *et al.*, 1995, Boëx *et al.*, 2006, Vermeire *et al.*, 2008). In these cases, logarithmic spacing of frequency bands would be likely to offer more natural sound perception than alternatives. Logarithmic spacing also spaces vowel formants fairly evenly along the electrode array. However, Di Nardo *et al.* (2010) measured pitch mismatch between the implant's frequency allocation and the perceived pitch of electrodes in a group of CI users and found that it was variable between individuals. They suggested adjusting the frequency allocation accordingly, which would require residual hearing to be present in the contralateral ear and would result in non-uniform frequency spacing in some cases.

6.4.2 Ideal Frequency Range

This study does not support the hypothesis that a broad frequency range, including all frequencies from 100 to 8500 Hz, is necessary to optimise perception of speech and music for CI users. It was found that some reduction of the frequency range could be tolerated, and indeed offered improved performance, although this was variable between individuals and different measures tested. The SII indicates that frequency bands in the middle of the speech frequency range are more important than those at either end of the range. The sentence and vowel test scores in this study are consistent with this finding for CI users. The BKB sentence test was performed with a male speaker, with F0 of approximately 175 Hz. The lower frequency boundary of 179 Hz gave better results over the group for this test than the boundaries of 225 and 142 Hz. For the vowel test, which was performed with a female speaker, the 142 Hz boundary offered poorer performance than the 179 and 225 Hz boundaries. This was an acute experiment and scores might have improved for the 142 Hz (L2) condition, should participants have had time to acclimatise to the different maps. So the results from experiment 2 do not necessarily mean that the 179 Hz boundary would be the best choice of the three boundaries tested in the long term. However, the results do indicate that inclusion of a very large frequency range is not the over-riding consideration for optimisation of the frequency allocation, as far as speech perception is concerned.

The sentence test results were slightly different at the upper end of the frequency range when compared with the lower end. For those with good pitch perception at the basal end, performance was good with the different upper boundaries tested (8500, 6747 and 5353 Hz) on the BKB sentence test. However, for those with poor PCT performance at the basal end, performance was poorer with the U2 (5353 Hz) boundary. These findings suggest that a smaller range is acceptable, so long as a sufficient range is included and pitch perception is good for the range which is used. These findings are based on the BKB sentence test with a male speaker. Female speakers and children were not tested.

The music ratings from experiment two suggest that frequencies at the lower end of the speech frequency range are also not critical for perception of the sung voice. Again, the L2 condition offered poorer performance than the L0 condition for a rating of natural sound quality for a male singer. The L2 condition was associated with a high pitch percept. This suggests that the issue of pitch shift had a greater effect on music quality than the extent of the frequency range, at least for the lower end of the range.

6.4.3 Considerations for Bilaterally Implanted Individuals

The reported results from the experiments conducted in this study all relate to unilaterally implanted CI users, who are profoundly deaf in both ears. There are additional considerations for bilaterally implanted CI recipients, when considering adjustment of the frequency allocation. For these people, differences in insertion depth can lead to a lack of fusion of auditory images and poor sensitivity to binaural cues (Kan *et al.*, 2015). So, whilst performance with their cochlear implants is still likely to be dependent on their pitch perception in different areas of the cochlea, the extent to which pitch mismatch has occurred will need to be considered too. More research could lead to a strategy for optimisation of the frequency allocation for bilaterally implanted recipients.

6.5 Pitch Perception in CI Users

6.5.1 Pitch Perception Measurements

The pitch perception abilities of CI users can be assessed in a number of different ways: an individual's ability to discriminate sound of different frequency can be measured or an individual's ability to perceive pitch direction changes (pitch contour) for pure tones or complex tones. Alternatively, CI users' abilities can be assessed in a more functional way, for example by assessing melody recognition or by rating the sound quality. In this study, measurements of discrimination and an ability to follow pitch contour were complemented by subjective ratings of music sound quality (naturalness) and musical pitch. A further functional measure of perceived pitch was included: participants were asked to adjust of the pitch of a song with different frequency allocations.

6.5.2 Participants' Abilities to Discriminate Pure Tones

Normal-hearing individuals are able to perceive small differences in frequency. For example, at 1 kHz, a typical frequency difference limen is 2 to 3 Hz (Moore, 2008b). Frequency difference limens are generally smaller for lower frequency sounds and larger for higher frequency sounds but even for tones of 8 kHz, the difference limen is between 50 to 100 Hz. By contrast, there are a small number of electrodes on a CI and the difference in centre frequency between neighbouring filters may be 0.4 to 0.5 octaves in the middle of the frequency range and even greater at the apical end. Some CI users are able to perceive sounds between the filter centre frequencies (see for example van Besouw and Grasmeder (2011)). However, if CI recipients are unable to discriminate the centre frequencies of neighbouring electrodes, their perception of pitch falls a long way short of that of normal-hearing individuals. In experiment 2, it was found that all participants were able to discriminate centre frequencies in the middle of the electrode array (although there were some errors for the contour scores) but in some cases adjacent electrodes at the ends of the electrode array could not be discriminated. Altogether 140 electrode pairs were tested and chance scores were found for discrimination in 11 pairs; 7 at the apical end and 4 at the basal end. For sounds comprised of frequencies that are allocated to these electrodes, pitch perception is severely compromised.

6.5.3 Electrode/region specific issues

Errors for the discrimination task related mostly to the extreme ends of the array. Similarly, 9 out of 25 electrode pairs at the apical end and 9 out of 24 electrode pairs at the basal end of the array, offered chance or below chance performance on the contour part of the PCT. As poor performance at the apical end may have been related to deep insertions, particularly with the standard electrode array, performance for participants with the standard and FLEX28 electrode arrays were analysed separately. Figure 92 and Figure 93 show the PCT scores for participants with the FLEX28 and standard electrode arrays respectively.

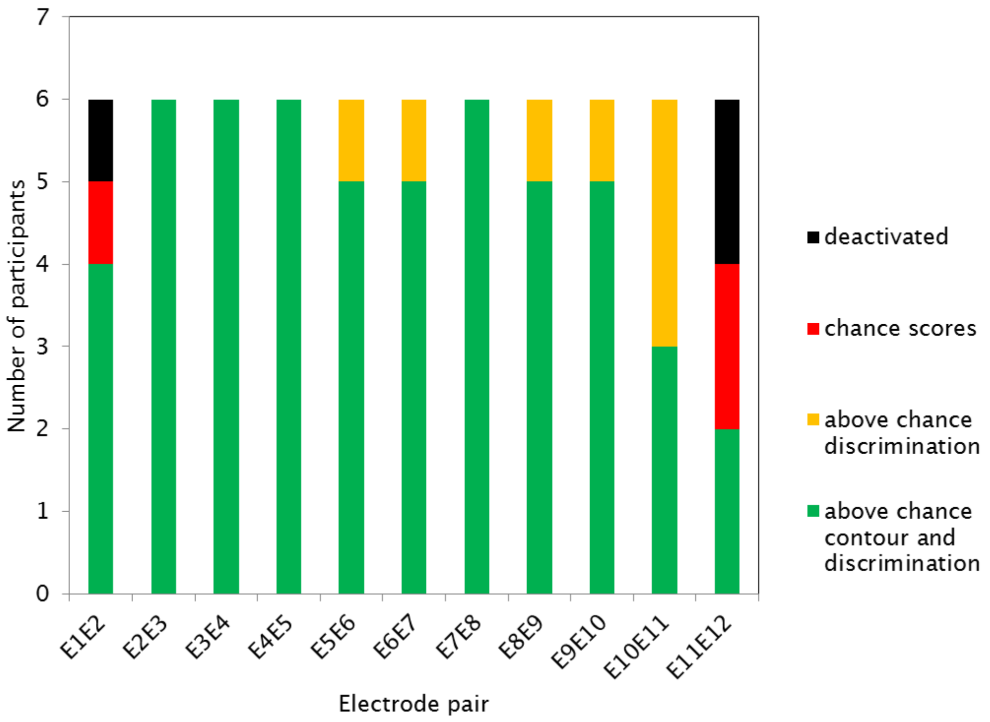


Figure 92 PCT scores for six participants with the FLEX28 electrode array in experiment 2

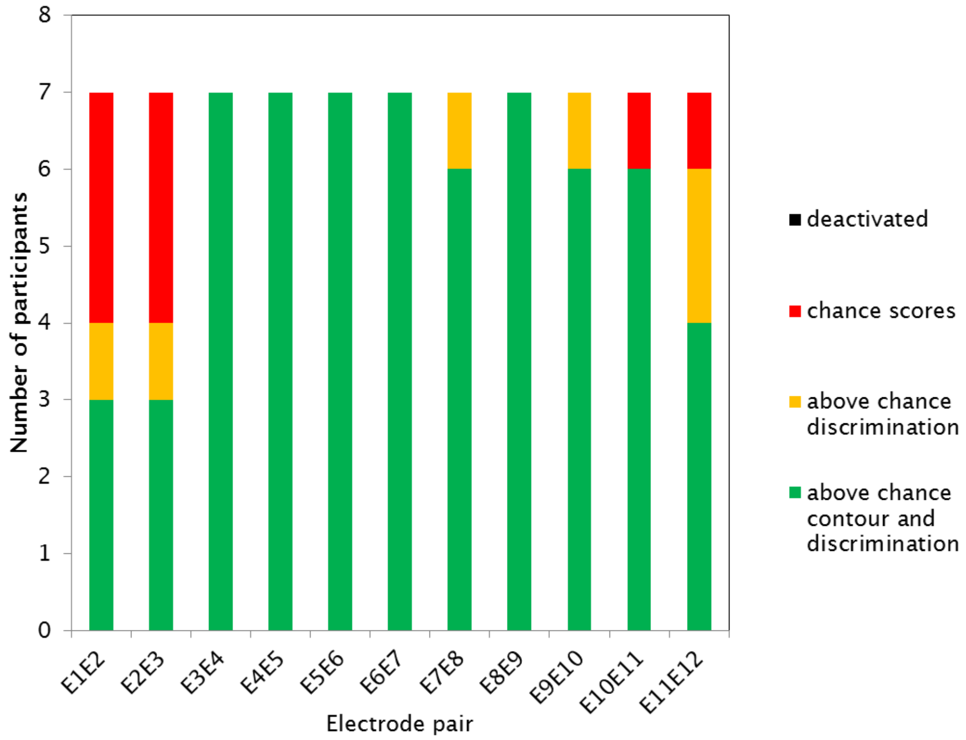


Figure 93 PCT results for seven participants with the standard electrode array in experiment 2

It can be seen that while all participants with the FLEX28 array performed above chance for both contour and discrimination for electrode pair E2E3, only three out of seven with the standard array were able to do this. With the FLEX28 array, performance was good at the apical end of the array for 10/12 electrode pairs but at the basal end of the array, performance was good for only 5/12 electrode pairs. With the standard array, performance was good for 6/14 apical electrode pairs and 10/14 basal electrode pairs. A larger number of CI recipients would need to be tested to see if these scores are representative of performance with these electrode arrays more generally. The FLEX28 PCT results from this study suggest that pitch perception is mostly good at the apical end with this electrode array. This length of array may prove to be a good choice for CI recipients with normal anatomy if problems at the basal end of the array can be reduced.

6.5.4 Physiology of Pitch Coding in CI Users

Limitations to place-pitch perception towards the apex of the cochlea have been predicted for CI users based on the anatomy of the cochlea (shorter length of the SG compared to the OC) and on the function of peripheral processes and SG cells (see for example Kalkman *et al*. (2014)). In addition, some deep insertions are associated with insertion into the scala vestibuli (Radeloff *et al*., 2008), which is known to have a negative effect on speech perception (Holden *et al*., 2013).

It was anticipated that perception of low frequency sounds would be better with the SG map than the Greenwood map in experiment 1, the SG map limited the area of the cochlea stimulated to approximately 1.5 turns, where better pitch perception is anticipated (Kalkman *et al*., 2014). However, the SG map was not completely successful at selecting electrodes which were associated with above chance electrode discrimination ability. Five electrodes were deactivated at the apical end of the array (over the whole group) as a result of implementation of the SG map, due to being deeply inserted. Four of these had chance electrode discrimination scores, but a further six apical electrodes were not deactivated, which were also associated with poor electrode discrimination scores. Five of these electrodes belonged to the three participants who showed benefit from the RFR map in experiment 1 part 2. These participants had the poorest electrode discrimination scores at the apical end and two of the three had deep insertions. Poor electrode discrimination scores at the apical end of the array may have been due to a limited population of SG cells, but another possibility is that these electrode arrays had migrated into the scala vestibuli, which is associated with poorer speech perception (Finley *et al.*, 2008).

6.5.5 Use of X-ray to guide tuning

In this study, insertion angles were estimated from post-operative X-rays, but this is not a straightforward procedure, as the round window cannot be visualised directly on the X-ray and in some cases only a subset of the electrodes can be visualised. Nevertheless, useful information can be found from this limited intervention. Electrodes can be visualised on a plain X-ray, although not necessarily all of them. If the most apical and basal electrodes are identified, a fairly accurate estimate of the insertion angle is possible, if the surgical technique does not vary greatly between surgeries/surgeons. In this centre, surgeons appear to have placed the most basal electrode relatively close to the end of the OC, typically. For the long MED-EL electrode arrays in experiment 1, this meant that the error in the estimate of the insertion angle (mean=6°) in experiment 1 was small compared to the total insertion angle.

In recent years there has been a move towards performing post-operative CT scans, to ascertain the position of electrodes, and the author suggests that this would be preferable if further position-related frequency allocation work is undertaken in future. Some CT scans offer excellent visualisation of the positions of electrodes, and both the insertion angle and the scala within which the electrode is located can be determined (e.g. Dorman *et al.* (2007), Finley *et al.* (2008)). This information would be highly desirable: it is known that scala vestibuli insertions offer poorer speech perception than scala tympani insertions and it would be helpful to see how scala placement affects pitch perception ability.

Chapter 7: Conclusions

This study investigated four different approaches to adjustment of frequency allocation in CI users. One of these was the use of a default allocation for all CI users. It was found that the use of a default frequency allocation does not result in optimal performance for all CI users, in spite of the fact that participants rated the pitch of the default map as close to normal.

Two alternative approaches involved adjusting frequencies to fixed positions in the cochlea. The first of these attempted to map frequencies to the frequency-position function of the normal cochlea. This resulted in poor performance for all participants. Another approach involved mapping the implant's frequency range to a reduced area of the cochlea. This resulted in poorer performance over the group when compared to the default allocation but some participants performed similarly with this map when compared to the default. The results of the first experiment suggest that participants had acclimatised to the default frequency allocation and that performance could not be improved by adjusting the frequency allocation to a closer 'pitch-matched' map. It was also found that electrode discrimination was poor for some participants at the apical end. However, allocating frequencies to a reduced area of the cochlea, which involved deactivating some apical electrodes, did not improve performance.

The fourth approach to adjustment of frequency allocation proved to be successful at improving performance, at least for some CI users. It was found that using a reduced frequency range in combination with logarithmic spacing of frequency bands resulted in improved performance for some CI users with poor electrode discrimination for apical electrodes.

In a further experiment, adjustment of frequency allocation based on pitch perception ability for different areas of the cochlea was explored further. It was found that speech perception could be improved by the selection of a frequency allocation based on measurement of pitch perception in the middle of the cochlea and at the basal end, using the 'Pitch Contour Test'. This indicates that rather than using a default frequency-to-electrode allocation for all CI users, the pitch perception ability in different areas of the cochlea should be considered when optimising the frequency-to-electrode allocation for individual CI recipients.

Appendices

Appendix 1

Optimizing frequency-to-electrode allocation for individual cochlear implant users

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Abstract

Individual adjustment of frequency-to-electrode assignment in cochlear implants may potentially improve speech perception outcomes. Twelve adult cochlear implant (CI) users were recruited for an experiment, in which frequency maps were adjusted using insertion angles estimated from post-operative X-rays; results were analyzed for ten participants with good quality X-rays. The allocations were a mapping to the Greenwood function, a compressed map limited to the area containing SG cells (SG), a reduced frequency range map (RFR) and participants' clinical maps. A trial period of at least six weeks was given for the clinical, Greenwood and SG maps although participants could return to their clinical map if they wished. Performance with the Greenwood map was poor for both sentence and vowel perception and correlated with insertion angle; performance with the SG map was poorer than for the clinical map. The RFR map was significantly better than the clinical map for three participants, for sentence perception, but worse for three others. Those with improved performance had relatively deep insertions and poor electrode discrimination ability for apical electrodes. The results suggest that CI performance could be improved by adjustment of the frequency allocation, based on a measure of insertion angle and/or electrode discrimination ability.

Appendix 1

I INTRODUCTION

Although cochlear implant users can achieve high levels of speech perception in quiet, a factor limiting performance in more demanding listening situations is pitch perception, which is generally poorer for cochlear implant (CI) users than for normal-hearing listeners (Gfeller *et al.*, 2007). One parameter that can be adjusted for individual device users is the allocation of frequencies to electrodes, including the frequency range used across the electrode array as a whole and individual electrode channels. The question arises as to whether this is desirable and likely to bring about improvements in performance. Potentially helpful adjustments could attempt to normalize pitch (to equate with normal hearing as far as possible), or to optimize the frequency regions which contribute most to speech intelligibility, or to compensate for neural survival or spread of electrical excitation in different regions. The purpose of the current study is to investigate adjustment of frequency-to-electrode allocation using different methods, including two based on insertion angle measurements from plain X-rays, to see if these produce improvements in performance.

A logical basis for optimizing frequency-to-electrode assignment is based on the finding that different frequency regions contribute to speech intelligibility to different degrees. The Speech Intelligibility Index or SII (ANSI, 1997) gives the relative significance of third-octave frequency bands for speech intelligibility. Each third octave band has an associated band importance value, which can be multiplied by an audibility value for the same third octave to predict speech intelligibility for a given speech signal or hearing loss. According to the SII model, third octave bands with center frequencies between 160 and 8000 Hz all contribute to speech intelligibility, suggesting that an optimal frequency map will include these frequencies, although the most important third octave bands are those with center frequencies of 1.6, 2 and 2.5 kHz. A study with normal-hearing participants listening to cochlear implant simulations found that the peak in the relative band importance function was approximately half an octave lower for cochlear implant simulations than for unprocessed speech (Whitmal and DeRoy, 2012). This suggests that for CI users, lower frequency sounds are relatively more important for speech intelligibility than higher frequency sounds, when compared to normal-hearing listeners. In a frequency allocation study with Nucleus cochlear implant users, Fourakis *et al.* (2007) suggested that the relative contribution of different frequency regions should be considered. They found that increasing the number of electrodes allocated to frequencies between 1100 and 3000 Hz could improve speech perception, possibly because the resolution of important speech frequencies in that range was improved.

Studies of frequency allocation in CI users have found that presenting a wide frequency range to the CI recipient does not always produce the best speech perception outcomes (Başkent and Shannon, 2005, Goupell *et al.* 2008, Fu and Shannon, 1999a). Başkent and Shannon (2005) conducted a frequency mapping study with MED-EL C40+ cochlear implant users and simulated different insertion depths. They found that, for simulated insertions between 20 and 25 mm, a reduced frequency range map with less spectral distortion resulted in better speech recognition. Similarly, Fu and Shannon (1999a) adjusted the frequency range available to participants in an experiment with Nucleus 22 CI users. When basal electrodes were selected, the frequency allocation which gave optimal performance had a lowest corner frequency of 753 Hz. Goupell *et al.* 2008), conversely, reduced the upper frequency boundary in a study of frequency allocation. They found that reducing the upper boundary from 8.5 to 4.9 kHz improved perception for one CI recipient and overall this map appeared to be a slightly better map than the default map. These studies suggest that presenting the whole speech frequency range may not be the most important consideration, when determining the ideal frequency allocation for a CI recipient.

A different basis for frequency allocation is suggested by Başkent and Shannon (2005), who reported that speech recognition is optimized when frequency information is presented to the normal acoustic tonotopic cochlear location, both for cochlear implant users and normal-hearing subjects listening to vocoded speech. The Greenwood function (Greenwood, 1990) describes the relationship between the location of cells along the basilar membrane and their 'characteristic' frequency, at which they respond maximally to the travelling wave along the basilar membrane, produced by the incoming sound. The frequency F (Hz) at a given position x (expressed as a proportion of cochlear length) is given by the equation:

$$F=A(10^{ax} - k) \qquad \text{equation 1}$$

where A=165.4, a=2.1 and k=0.88

'A' represents frequency in Hertz; 'a' represents the slope of the straight portion of the frequency-position function and 'k' gives a lower frequency limit of 20 Hz.

Appendix 1

A number of studies of either cochlear implant users or vocoded speech have suggested a 'matching effect', whereby performance is optimized when the frequency map of the implant corresponds to the frequency map expected by the recipient from their memory of acoustic hearing (Dorman *et al.*, 1997, Shannon *et al.*, 1998, Fu and Shannon, 1999c, Fu and Shannon, 1999a, Fu and Shannon, 1999b, Başkent and Shannon, 2003, Başkent and Shannon, 2004). Dorman *et al.* (1997) performed a five channel simulation study with normal-hearing listeners and found that the best speech perception was obtained when the frequencies of sine waves output from each channel of a processor corresponding to the simulated insertion depth (25 mm) were matched to the normal tonotopic frequency; performance was reduced when the simulated insertion depth was reduced to 22, 23 or 24 mm, which produced a basal spectral shift. However, studies with CI users offered more mixed results: speech perception was found to vary as a function of frequency allocation but the frequency map offering the best performance did not always correspond to the normal acoustic tonotopic map, but to the allocation closest to that in the recipient's clinical processor.

It is unclear whether the frequency-position function of the impaired cochlea can be well represented by the Greenwood function and hence used as a basis for deriving the optimal frequency to place map for CI users. It has been found that hair cells are not necessary for a successful CI outcome Fayad and Linthicum, (2006) and SG cells are likely to be the means by which the auditory nerve is accessed for CI users. SG cells are arranged over a shorter distance along the length of the cochlea than hair cells (Kawano *et al.*, 1996, Stakhovskaya *et al.*, 2007, Sridhar *et al.*, 2006). The function relating frequency matched points along the OC and SG has been described by Sridhar *et al.* (2006):

$$y = -5.7.10\wedge - 5x^3 + 0.0014x^2 + 1.43x \qquad \text{equation 2}$$

Where y = % distance from the base for the SG and x = % distance from the base for the OC.

The function reflects the curvature of the cochlea such that the equation maps from the angle of rotation for the OC to the angle of rotation for the SG very closely, as given in Stakhovskaya *et al.* 2007), figure 9. Whilst the Greenwood function suggests that pitch changes uniformly with length along the OC over approximately 90% of its length, equation two suggests that pitch changes relatively uniformly with length along approximately 80% of the SG and thereafter pitch decreases more rapidly towards its apical end. A frequency-matched map for the SG is given in Stakhovskaya *et al*. (2007), which is similar to the Greenwood map over most of the basal turn but frequency drops off more rapidly with angle of rotation in the middle turn.

A number of groups have investigated the frequency-position function of the implanted cochlea by asking unilaterally implanted CI users with significant residual hearing in their contralateral ear to match the frequency of a tone presented acoustically, to their contralateral ear, to the pitch percept associated with unmodulated pulse trains presented to individual CI electrodes (Dorman *et al*., 2007, Baumann and Nobbe, 2006, Boëx *et al*., 2006, Simpson *et al*., 2009, Vermeire *et al*., 2008, Carlyon *et al*., 2010, Baumann *et al*., 2011, Di Nardo *et al*., 2008, Di Nardo *et al*., 2010). Such experiments are not necessarily easily performed: Baumann *et al*. (2011) reported that a reliable pitch comparison for CI users was difficult to achieve and this was attributed to the neural spread of excitation created by electrical stimulation. There is substantial variability in such measurements both within and between individual CI users (Baumann and Nobbe, 2006). Some studies found the match to be approximately equivalent to the Greenwood function (Carlyon *et al*., 2010, Vermeire *et al*., 2008) whilst others found matches were significantly below this, even by an octave or more for some participants (Dorman *et al*., 2007, Boëx *et al*., 2006, Simpson *et al*., 2009, Baumann and Nobbe, 2006). Carlyon *et al*., (2010) argued that frequency range effects routinely occur in pitch-matching experiments and this may account for some variability between studies; other differences between studies include differences in radiological technique and different levels of residual hearing amongst participants. Differences in the shape of the frequency-position function were also reported. In some cases the relationship between frequency and angular position was consistent with the Greenwood function; in other cases the functions were flatter towards the apex, suggesting little or no change in pitch percept between apical electrodes (Boëx *et al*., 2006, Dorman *et al*., 2007, Baumann and Nobbe, 2006). Flattening of the frequency position function towards the apex is neither consistent with a frequency-matched map for the OC (Greenwood function) nor the SG (Stakhovskaya *et al*., 2007) and may be related to a loss of SG cells (Baumann *et al*., 2011). Baumann and Nobbe found that the frequency-position function was more linear than expected, although they only tested apical to mid electrodes due to the limited amount of residual hearing of their participants. Di Nardo *et al*. (2010) found mismatch between frequencies allocated to each electrode and the perceived frequency of the electrode when stimulated; the amount of mismatch varied considerably between participants but was correlated with speech perception performance.

An integral part of determining an individual's frequency-to-place map is identifying the position of implanted electrodes relative to the cochlea. Variations in cochlear size give rise to considerable variability in insertion angles, for the same length of electrode array (Radeloff *et al.*, 2008) and hence it is not sufficient to assume the angular position of the electrodes from the length of the electrode array. Additionally, it is possible for the electrode array to follow a different trajectory to the intended one and to enter the scala vestibuli, which may affect the position of electrodes relative to the basilar membrane (Finley *et al.*, 2008, Skinner *et al.*, 2007). Cohen *et al.*, (1996) suggested a clinical method for determining the positions of the electrodes from a plain X-ray. This requires the superior semicircular canal and vestibule to be visualized on the X-ray so that a reference line can be drawn which passes through the apex of the superior semicircular canal and the vestibule, cutting the electrode array at the position of the round window. A pitch-matching study by Boëx *et al.* (2006) used Cohen's method to determine the site of the round window but found the insertion angle of the electrodes from a reference 0˚ line, which was drawn between the estimated position of the round window and the center of the first turn of the spiral made by the electrode array, rather than by comparison with a template as in Cohen's method.

Calculation of the Greenwood function requires knowledge of the length of the basilar membrane, or distance as a proportion of basilar length but this cannot be visualized on a post-operative X-ray. There is a considerable amount of variability in the size of the cochlea between individuals, especially in the length of the OC (Ulehlova *et al.*, 1987). There is less variability in the number of turns and hence a calculation based on an estimation of the electrode position relative to the proportion of basilar length may be more suitable, although this gives a slightly different result from expressing the function in millimeters. In the study by Dorman *et al.* (2007) the recipient had a CT scan performed post-operatively and this enabled the Greenwood function to be expressed in millimeters, the value of '*a*' in the function to be calculated and the individual electrode positions to be ascertained. If the Greenwood function had been expressed as a proportion of cochlear length, with '*a*' as 2.1 as suggested in Greenwood (1990), higher values for the characteristic frequencies corresponding to individual electrodes would have been obtained, with the difference being in excess of half an octave for some electrodes.

Even if the frequency-to-place map is determined accurately for individual cochleae, it is still possible that a matched frequency-to-place map may not represent the ideal frequency allocation for individual CI users: implants differ in insertion depths (Radeloff *et al.*, 2008) and if the insertion depth is shallow, some compression is preferable over matching to the tonotopic frequencies (Başkent and Shannon, 2005); pitch sensitivity may be non-uniform along the length of the electrode array, (Boyd, 2011, Gani *et al.*, 2007, Nelson *et al.*, 1995) which would result in non-uniform spacing of consecutive center frequencies of the map; fitting a matched map in such cases is likely to be difficult and as yet there is little evidence to suggest that it would be helpful. A further issue is that pitch sensitivity may be reduced towards the apex, suggesting that important speech frequencies should be mapped away from this area, at least for some CI recipients.

Manufacturers' guidelines typically recommend a default map, which maps the speech frequency range to the available electrodes and therefore many cochlear implant maps are not 'matched'. However, if the frequency allocation is not matched and speech perception is adversely affected as a result, performance with the map may still improve with time. (Rosen *et al.*, 1999)) found that performance with a frequency shifted map increased from near zero to about one-half the performance in the unshifted condition, after just three hours of experience. Other studies have also observed acclimatization effects (Li *et al.*, 2009, Goupell *et al.*, 2008, McKay and Henshall, 2002, Fu and Shannon, 2002, Sagi *et al.*, 2010a, Svirsky *et al.*, 2004) in normal-hearing participants listening to CI simulations and in CI recipients. Svirsky *et al.* (2004) found that for three post-lingually deafened adults, acclimatization for vowels had occurred after one day, one month and three months post activation respectively, but for a pre-lingually deafened adult, up to 24 months was needed for acclimatization to occur. Sagi *et al.* (2010) reported that some acclimatization occurred following a severe basal spectral shift, for three CI users who were exposed to a shifted map for three months; two could shift their internal representations to the new sound within one week but one had not completely shifted their representation after three months.

In summary, it is possible that a frequency allocation matched to the CI recipient's internal frequency map, or one adjusted to make best use of remaining SG cells, may offer better speech perception than a default map, which maps the speech frequency range (100 – 8500 Hz) to the available electrodes.

Adult cochlear implant users with at least one year's experience with their implant were recruited. Participants attended the clinic on four occasions and were tested with four different frequency maps, on two speech perception tasks. Three of the maps were tested immediately after fitting and again after at least six weeks, during which participants were encouraged to use the study map. The fourth map was tested immediately after fitting only, during the final session. The maps with take-home experience were a mapping to the Greenwood function; a compressed map limited to the area likely to contain SG cells ('SG'), and the recipient's own clinical map. The Greenwood and SG maps were dependent on measurement of the insertion angles of the electrodes, from participants' routine post-operative X-rays. Finally, a reduced frequency range map was tested in the final session, which mapped the most important speech frequencies (the third octave bands with center frequencies from 200 to 5000 Hz) to all the available electrodes, with logarithmic frequency spacing. This served to increase resolution for the most important speech frequencies, as suggested by (Fourakis *et al.*, 2007), whilst reducing the frequency range allocated to the apical electrodes, where pitch confusions may be present (Gani *et al.*, 2007).

II METHODS

A Participants

Twelve MED-EL cochlear implant users with standard electrode arrays, who were available to attend, were recruited for the experiment. The MED-EL standard electrode array has 12 electrodes, each spaced 2.4 mm apart with an active length of 26.4 mm. This device was chosen due to the flexibility of the frequency allocation setting and the long length of the electrode array. All participants were post-lingually deafened adults, had at least twelve months experience with their device and scored at least 80% correct on the BKB sentence test (Bench *et al.*, 1979) in quiet, at the start of the study. All had cochleostomy insertions with the exception of P2, who had a round window insertion. Participants' details are shown in TABLE I.

TABLE I

Participant	Age at Start of Study	Gender	Etiology	Duration of implant use (years)	Strategy	Unilateral or Bilateral
P1	64	Male	Menieres	12	FSP	Bilateral
P2	65	Male	Unknown progressive	1	FSP	Unilateral
P3	59	Female	Hereditary	2	FSP	Unilateral
P4	61	Male	Hereditary	1	FSP	Unilateral
P5	41	Female	Hereditary	3	FS4	unilateral
P6	56	Female	Hereditary	1	FS4	Unilateral
P7	61	Male	Unknown progressive	2	FSP	Unilateral
P8	41	Female	Hereditary	3	FSP	Unilateral
P9	68	Female	Infection	3	FSP	Unilateral
P10	65	Female	Hereditary	3	FS4-p	Unilateral
P11	51	Female	Bilateral skull fracture	2	FSP	Unilateral
P12	83	Female	Otosclerosis	1	FSP	Unilateral

Ethical approval for the study was obtained from the NHS National Research Ethics Service (reference 11/SC/0291). Cochlear implant recipients whose X-rays were analyzed consented for their pooled anonymized data to be published. Those who participated in the experiment gave written informed consent.

B Radiological assessment

A method of estimation of electrode insertion angle from post-operative X-rays was first developed and validated. These are routinely collected and involve minimal radiation exposure. An experienced consultant radiologist reviewed X-rays for CI recipients with MED-EL devices, which had been implanted locally, and confirmed that these were of sufficient quality for individual electrodes to be identified in the majority of cases. Five X-rays were selected for analysis with good resolution and appropriate projection angles. One was a round window insertion; four implants had been inserted via a separate cochleostomy. In these cases the radiologist identified the position of the round window from the morphology; in some cases it was possible to identify the position of the superior semicircular canal and the vestibule, and it was found that a line joining these two points cut the electrode array at the position of the round window, thereby confirming that the position of the round window had been identified correctly. The images were imported into Microsoft PowerPoint (by a clinical scientist) and the center of each turn was determined from the center of an oval positioned over the electrode positions, using the standard Windows drawing tools. The average angle between the most basal electrode and the round window, and the relative positions of the electrodes were found. The angles were measured relative to the position of the line joining the center of each oval and the round window, as in Boëx *et al.* (2006). The position of the round window was further verified by superimposing the electrode positions onto a template of the cochlea from Kawano *et al.* (1996). The average data for electrode angles is shown in figure 1, in comparison with the electrode angles given for the participant in Dorman *et al.* (2007), who had a cochleostomy insertion.

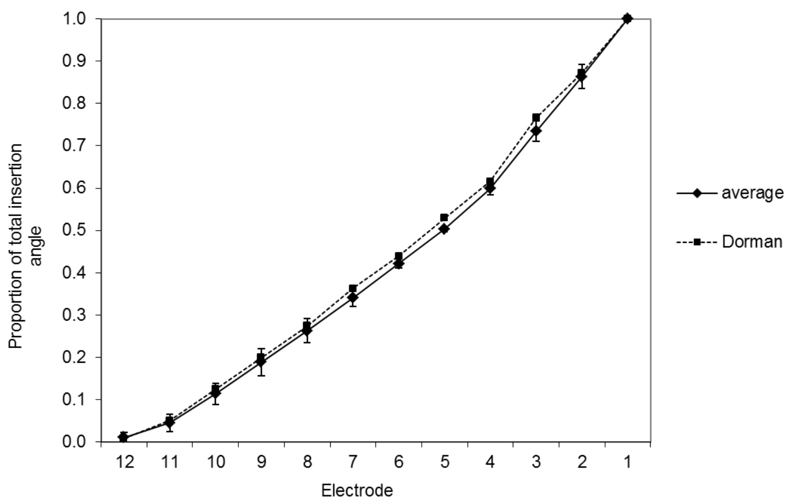


Figure 1 Mean insertion angles as a proportion of the total insertion angle (measured from the round window) for electrodes for five X-rays included in the review and those for the recipient in Dorman *et al.* (2007). Error bars = 1 standard deviation.

The data in figure 1 shows that the angles between electrodes were relatively constant in both turns but were larger in the middle turn, as expected (electrodes 1 to 4, typically) and the results for this study were very similar to the angles for the participant in Dorman *et al.* (2007). The most basal electrode was frequently close to the round window and had a very small insertion angle (approximately 1% of the total insertion angle).

For the participants in the experiment, only the angle between the most basal and most apical electrode was measured. The angles of the intermediate electrodes were assumed to be at the same proportions of the total insertion angle as for the reviewed X-rays. For fully inserted arrays, the angle between the round window and the most basal electrode was assumed to be at 1.1% of the total insertion angle, which was the mean value for this angle in the earlier review. For three electrode arrays which were reported as partially inserted by the surgeon, information about the insertion from the surgeon's intra-operative report was used to estimate the angle between the most basal electrode and the round window. Details can be found in TABLE II.

TABLE II

Participant	Image type	Number of intra-cochlear electrodes (surgeon's report)	Number of intra-cochlear electrodes (radiologist's report)	Angle between apical and basal electrodes	Distance between round window and basal electrode	Estimated insertion angle	Measured insertion angle based on radiologist's information
1 left	Film	12	12	602˚	Not known	609˚	Not available
1 right	Film	8-9	9	305˚	0 mm	308˚	339˚
2	Digital	12	12	635˚	~ 1 mm	642˚	640˚
3	Digital	12	12	564˚	1 – 2 mm	570˚	569˚
4	Digital	12	12	698˚; scaled up from electrodes in the basal turn	~ 1 mm	706˚	Not available but likely to be less than 706˚
5	Digital	11	10	441˚	1 – 2 mm from E10	441˚	437˚
6	Digital	11	11	482˚	Between E11 and 12	482˚	485˚
7	Digital	12	12	602˚	~ 3 mm	609˚	627˚
8	Film	12	12	697˚	< 1 mm	705˚	699˚
9	Film	12	12	675˚	< 1 mm	683˚	677˚
10	Digital	12	11	432˚	Between E11 and E12	437˚	428˚
11	Digital	12	12	565˚	<1 mm	571˚	567˚
12	Digital	12	11	562˚	E12 very close to round window	568˚	560˚

Of the 12 CI recipients who were recruited, ten had X-rays which were of sufficient quality to allow all the electrodes and the position of the round window to be identified by the consultant radiologist, who had performed the X-ray review. In these cases, the difference between the estimated angle between the round window and the most basal electrode, and the angle determined by the consultant radiologist, was small (mean absolute error = 6.1˚, range 1-18˚). The estimated insertion angle was used to calculate the frequency maps used in the experiment and was also included in the data analysis. In the case of the two participants with poor quality X-rays (P1 bilateral and P4 unilateral), both the clinical scientist and the radiologist had difficulty visualizing some electrodes for these participants. Their data were excluded from the data analysis.

Figure 2 Post-operative X-ray for P3: all electrodes were visualized

C Frequency allocations

Four different maps with different frequency allocations were tested during the experiment. One of these was the participant's everyday clinical map, usually the default map, which was presented as a new map and trialed for at least six weeks so as to reduce bias based on the idea that a new map would be better. The relationship between electrode number and lower frequency boundary, for the default map, is a fourth order polynomial function, which allocates a larger proportion of the frequency range to the apical electrodes than the basal electrodes, consistent with a more rapid decrease in pitch in the middle turn, as indicated by the SG frequency-matched map (Stakhovskaya *et al.*, 2007). The three alternative maps were a mapping to the Greenwood function, using the function expressed as a proportion of cochlear length (a=2.1; A=165.4; k=0.88) and data from table two of Kawano *et al.* (1996) to convert between angles and a proportion of cochlear length. Kawano *et al.*'s data were used as the position of the electrodes relative to the round window, for the X-rays in the review, showed very good agreement with the cochlear template, shown in figure 4A of Kawano *et al*.

Another alternative map was calculated using equation 2 above from Sridhar *et al.* (2006). This equation was applied to the proportion of cochlear length (along the OC), prior to the calculation of the Greenwood function for the 'spiral ganglion' ('SG') map, such that the Greenwood function was calculated as a proportion of SG length. The result was a compressed map, allowing the processor's frequency range to be presented to the area of the cochlea over which SG cells are likely to be present. The insertion angle required to map all of the processor's frequency range was 746° for the Greenwood map and 526° for the SG map. For both the Greenwood and SG maps, the function relating electrode number to lower frequency boundary was exponential ($R^2 = 0.9991$ for the Greenwood map and $R^2 = 0.9997$ for the SG map, for an insertion angle of 526°). It was anticipated that the SG map may be beneficial for those with shallow insertions, for whom the polynomial default frequency map may be inappropriate, and the Greenwood map would result in truncation of the frequency range. It was also anticipated that the SG map may be helpful for those for whom pitch sensitivity is poor for apical electrodes and for CI recipients for whom a frequency-matched map lies significantly below the Greenwood function. The final alternative map was a reduced frequency range ('RFR') map, with logarithmic frequency spacing of center frequencies: range 178 to 5612 Hz, using all available electrodes. The map attempted to enhance resolution for the most important speech frequencies, whilst reducing the frequency range mapped to the apical electrodes, which may have less pitch sensitivity. The frequency range offered for the three alternative maps did not exceed the default frequency range (100 – 8500 Hz). The clinical map had the default shape in all cases: it used the default range of 100 – 8500 Hz in nine cases and 70 – 8500 Hz in one case (P8). The center frequencies (Hz) of individual channels for the study maps for participants P10 (shallowest insertion) and P8 (deepest insertion) are shown in TABLE III.

TABLE III Channel center frequencies (Hz) for participants P8 and P10

Electrode	1	2	3	4	5	6	7	8	9	10	11	12
P10 clinical	154	278	448	673	986	1406	1978	2714	3858	5238	7335	Off
P8 clinical	125	234	385	582	840	1182	1631	2227	3064	4085	5656	7352
P10 Greenwood	720	992	1356	1927	2535	3342	4325	5656	7352	off	off	off
P8 Greenwood	182	304	489	760	1107	1559	2264	3452	5164	7346	off	off
P10 SG	216	317	479	736	1103	1586	2345	3468	5482	7352	off	Off
P8 SG	off	off	136	230	370	569	932	1606	2805	5932	7352	off
P10 RFR	210	288	393	536	742	1006	1386	1883	2623	3497	4896	off
P8 RFR	206	273	366	487	651	865	1149	1532	2042	2723	3676	4902

Appendix 1

The frequency range varied for the Greenwood and SG maps between participants as these maps were in fixed locations and the frequency range therefore depended on the insertion angle of the most apical electrode. Participants with deeper insertions had access to a larger frequency range than those with shallow insertions for the Greenwood map (see table 3). Participants had one or two basal electrodes deactivated for the Greenwood and SG maps as the frequencies calculated for the most basal electrodes were beyond the permitted frequency range; similarly participants had one or two apical electrodes deactivated for the SG map but never more than three electrodes deactivated in total. The mean number of electrodes was 11.5 for the clinical and RFR maps (range 10–12); 9.5 for the SG map (range 9-10) and 9.7 for the Greenwood map (range 9-10). Deactivation of electrodes produced increases in the rate of stimulation for the remaining active electrodes, especially with the FSP strategy. Additionally the number of 'fine structure channels' (apical electrode channels in which pulse rate is not fixed but is tied to changes in frequency), was increased in six cases with the SG map and in one case with the Greenwood map and the RFR map; it was reduced in seven cases with the Greenwood map and two cases with the RFR map; for the participants with the FS4 and FS4-p strategies (in which the number of fine structure channels is usually four), the Greenwood map resulted in a reduction in the number of fine structure channels.

Participants attended the center on four occasions and a study map was downloaded to their processor during each of the first three sessions, to enable them to try the map for the trial period: Greenwood, SG or clinical. The order in which participants tried these maps was balanced and assigned pseudo-randomly. During the final session participants were tested with the RFR map, without any time to acclimatize, as this map was included in the experiment as an additional map, after the data collection had commenced. Trials of the first three maps lasted for at least six weeks (mean time of use = 7.9 weeks, range 6-13 weeks), during which participants were encouraged to use the study map but could return to their clinical map if they wished to. Instructions for participants were 'Please use the new map as much as you feel able to over the next few weeks and compare it with your everyday map in programme… It may take some time to get used to the new map (at least a few days), so please do give it a good try. If you find the sound quality unacceptable, however, do feel free to return to your everyday map.'

D Assessments

Three outcome measures were used with each map: two speech perception tasks, which have previously been found to be sensitive to changes of frequency allocation (see for example, Başkent and Shannon, 2004), and a subjective rating of sound quality. The speech perception measures were the BKB sentence test (Bench *et al*., 1979) in speech-shaped noise and an eight alternative forced choice test of vowel perception. The BKB sentence test was performed initially after fitting and at the end of each trial, whereas the vowel test was performed at the end of each trial only, or immediately after fitting for the RFR map. The map quality questionnaire was completed at the end of each map trial and was therefore only completed for the clinical, SG and Greenwood maps. Additionally, electrode discrimination was assessed for each pair of neighboring electrodes.

The BKB sentence test was spoken by a male speaker and presented in speech shaped noise, which was based on the male voice. The test was performed in a sound treated room, from a Tannoy V12 BLK loudspeaker at 0˚ azimuth, with each participant seated on the calibrated spot. Speech was presented at 65 dB(A); calibration was to the speech shaped noise at the calibrated spot. The signal-to-noise ratio (SNR) used for the experiment, for each individual, was determined adaptively using single lists of sixteen sentences with the clinical map, such that the SNR gave a score between 60 to 70% correct with the clinical map on a single list. Two lists of sixteen sentences each were presented to assess performance each time the test was administered giving a total maximum score of 100 key words correct, using loose scoring. Patients at the center had previously performed the test on several occasions, with different lists each time, so a learning effect on the test was unlikely. List numbers were incremented to avoid repetition.

The vowel identification test was an eight alternative forced choice test, spoken by a female speaker, and presented using the same soundfield arrangement as for the BKB sentence test, with mean vowel presentation level of 65 dB(A). Each vowel was preceded by /h/ and followed by /d/, giving the following tokens: 'heed', 'head', 'hid', 'heard', 'hood', 'who'd', 'had' and 'hard'. Each token was presented five times in random order during each test. Participants selected their choice of token from a graphical user interface on a touch screen monitor.

The map quality questionnaire contained only two questions. 'How often have you used the new map?' had five possible answers of 'very little', 'less than half the time', 'about half the time', 'more than half the time' and 'all the time', and the participant ticked a box to give their answer. The second question, 'How do you rate the sound quality of the new map?' was recorded on a visual analogue scale, which extended from 'very poor' on the left side of the page to 'very good' on the right side of the page.

The electrode discrimination test was administered as a variation of the pitch test from the South of England Cochlear Implant Center Music Test Battery (van Besouw and Grasmeder, 2011). The pitch test is a three interval, three alternative forced choice test. The participant is asked to identify the odd note out when three notes, each of one second duration, are presented consecutively, separated by a short gap, in random order. The original test runs adaptively, using a 'two-down, one-up' procedure, which converges on 71% correct, but for this study it was re-configured for the method of constant stimuli. Eight trials were run for each pair of electrodes, and the electrode pairs were tested in a pseudo-randomized order. Stimuli were pure tones of 1125 and 1500 Hz: in each case only the two electrodes being tested were activated in the participant's map, and the frequency boundaries were adjusted so that these frequencies represented the center of each filter. The strategy was adjusted to high definition Continuous Interleaved Sampling (HD-CIS) and each pair of electrodes was loudness balanced at 90% of the dynamic range prior to the test; during the test the full dynamic range was used. Tones were presented via circumaural headphones, Sennheiser HD570, worn over the processor. The reference tone was calibrated to 60 dB(A) and the comparison tone was calibrated to the equivalent level within the processor ± 1 dB, taking account of the microphone frequency response and the processor's frequency shaping filter. Additionally, intensity level was roved by ± 3 dB.

III RESULTS

Statistical analysis was performed using repeated measures ANOVA and ANCOVA where results were normally distributed and Mauchly's test of sphericity gave a non-significant result; Pearson's correlation coefficient was used for correlations between variables which were normally distributed. Where the Shapiro-Wilk showed that data were not normally distributed, Friedman's test and Wilcoxon's signed rank test were used. The effect size has been reported as 'r' for this test. The effect size was calculated from the F-ratio for within-subjects contrasts for post-hoc tests following ANCOVA.

Reported map use from the map quality questionnaire is shown in figure 3 for the clinical, SG and Greenwood maps. The map quality questionnaire was not completed for the RFR map as this map was tested acutely during the last session only. Friedman's test confirmed that there was a significant effect of frequency allocation on the reported amount of use [chi-squared(2)=13.3, $p<0.001$]. Wilcoxon signed rank tests showed that the Greenwood map was used significantly less than the clinical map [$Z=-2.724$, $p=0.006$, $r=-0.61$, a large effect], as was the SG map [$Z=-2.116$, $p=0.034$, $r=-0.47$, a medium effect].

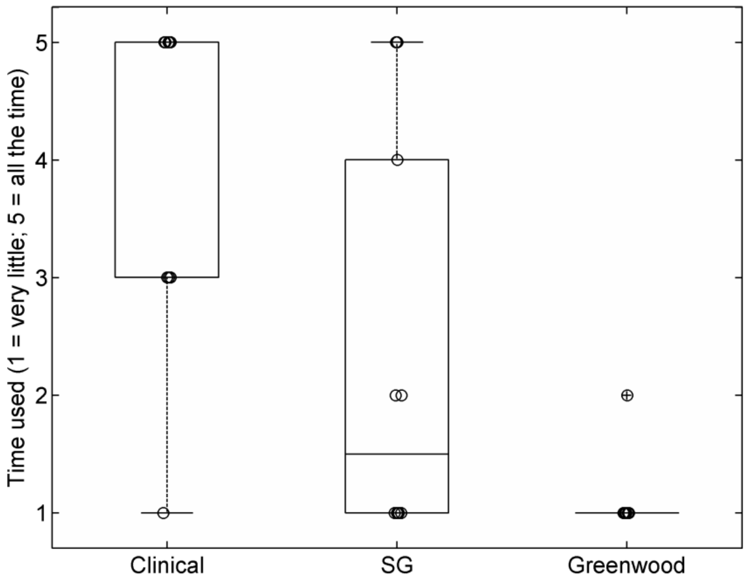


Figure 3 Map use with the clinical, SG and Greenwood maps as reported on the map quality questionnaire at the end of each trial period. Boxes indicate the interquartile range; the solid line within each box indicates the median value. An outlier is displayed as a cross. Individual data points are indicated by small circles.

Participants' rating of the quality of each map is shown in figure 4. A repeated measures ANOVA confirmed that there was a significant effect of frequency allocation on map sound quality rating [$F(2,18)=14.5$, $p<0.001$]. Post-hoc tests showed that the clinical map was rated more highly than the SG map [$p=0.006$, $r=0.76$] and the Greenwood map [$p<0.001$, $r=0.91$], both large effects, but the difference in map sound quality rating between the SG and Greenwood maps was not significantly different [$p=0.074$].

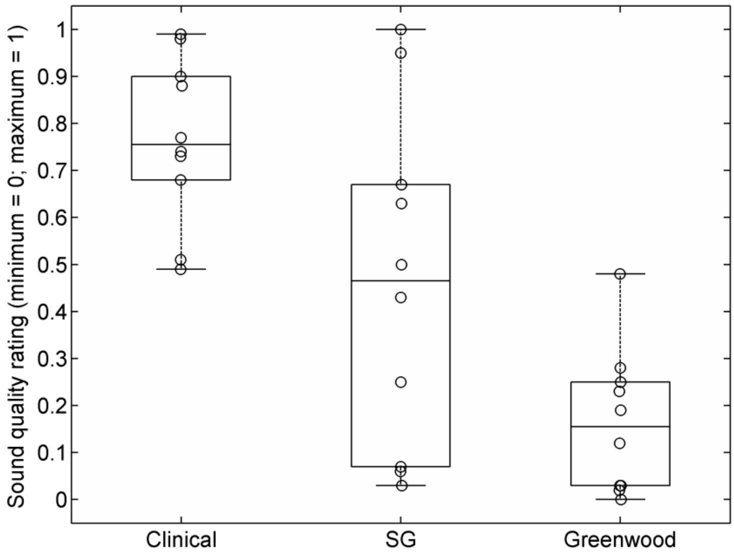
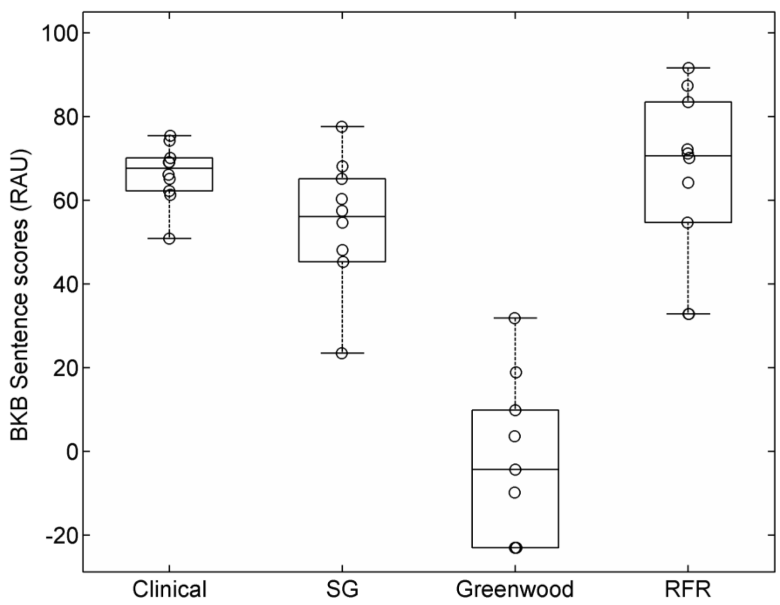


Figure 4 Map quality ratings for the clinical, SG and Greenwood maps as reported on the map quality questionnaire at the end of each trial period. Boxes indicate the interquartile range; the solid line within each box indicates the median value. Individual data points are indicated by small circles.

BKB sentence scores for the clinical, SG and RFR maps were found to be normally distributed but results for the Greenwood map were not normally distributed as there was a floor effect for this map, both before and after acclimatization. In view of this, the BKB sentence data were transformed using a rationalized arcsine unit (RAU) transform (Studebaker, 1985). Following this, data were normally distributed for all maps.

Results for the BKB sentence test were analyzed to see if there was any change in score for the two test occasions. Paired *t*-tests (2-tailed) were performed for the clinical, SG and Greenwood maps, which were tested both before and after the trial period. No change in sentence perception was shown for any of the maps between the two test intervals [clinical map $t(9)=-2.204$, $p=0.055$, SG map $t(9)=-0.971$, $p=0.357$, Greenwood map $t(9)=0.171$, $p=0.868$]. In view of this, and the fact that the RFR map had been tested without any acclimatization, scores for the initial test session were compared for all four maps. Results are shown in figure 5. Repeated measures ANCOVA was performed. The within subject factor was frequency allocation and the co-variates were the estimated insertion angle and the signal to noise ratio used for each participant in the test. ANCOVA confirmed a significant main effect of map frequency allocation [$F(3,21) = 19.58$, $p<0.001$]. There was also a significant interaction between the map frequency allocation and the estimated insertion angle [$F(3,21) = 14.62$, $p<0.001$] whilst there was no interaction between the map frequency allocation and the signal to noise ratio used in the test [$F(3,21) = 0.311$, $p=0.817$]. There was no independent effect of estimated insertion angle [$F(1,7) = 4.46$, $p=0.073$] or signal to noise ratio used [$F(1,7) = 4.89$, $p=0.063$]. The fact that there was no effect of signal to noise ratio used, suggests that participants experienced similar changes in sentence perception ability as a result of adjustment of the frequency allocation, even though performance on the test was variable with the clinical map. However, as there may have been a relationship between the estimated insertion angle and the SNR used in the test, linear regression was performed with the estimated insertion angle as the independent variable and the SNR as the dependent variable (both of these variables were normally distributed). No significant correlation was found [$r=0.098$; $p=0.787$].

Post-hoc tests, following the ANCOVA, showed that performance was better with the clinical map than with the SG map [$p = 0.004$, $r=0.56$] and also the Greenwood map [$p<0.001$, $r=0.97$], both large effects; there was no difference in performance between the clinical and RFR maps [$p=0.962$]. Performance with the SG map was better than performance with the Greenwood map [$p<0.001$] but not significantly different to that with the RFR map [$p=0.059$]. Performance was poorer with the Greenwood map than with the RFR map [$p<0.001$].



Appendix 1

Figure 5 BKB sentence scores for each map at the first test occasion, prior to acclimatization. Boxes indicate the interquartile range; the solid line within each box indicates the median value. Individual data points are indicated by small circles.

The interaction between the estimated insertion angle and sentence score was strongest for the SG [r=-0.809, p=0.005] and Greenwood [r=0.800, p=0.005] maps but also significant for the RFR map [r=0.722, p=0.018]. There was no correlation between the estimated insertion angle and BKB score with the clinical map, as expected [r=-0.441, p=202]. For the SG and Greenwood maps, the direction of the correlation reflected the magnitude of change in frequency-to-electrode mapping, which was experienced by participants when trying these maps.

Three participants (P2, P9 and P12) showed individual improvement on the BKB sentence test with the RFR map when compared with their clinical map; these improvements equaled or exceeded the critical differences for the test, which are given by Martin (1997). However, three participants also performed significantly worse with this map (P5, P6 and P11). All participants performed worse with the Greenwood map than with their clinical map, whilst four performed worse with their SG map and six performed at a similar level. Comparisons between the clinical map and the other maps for individual participants are shown in figure 6.

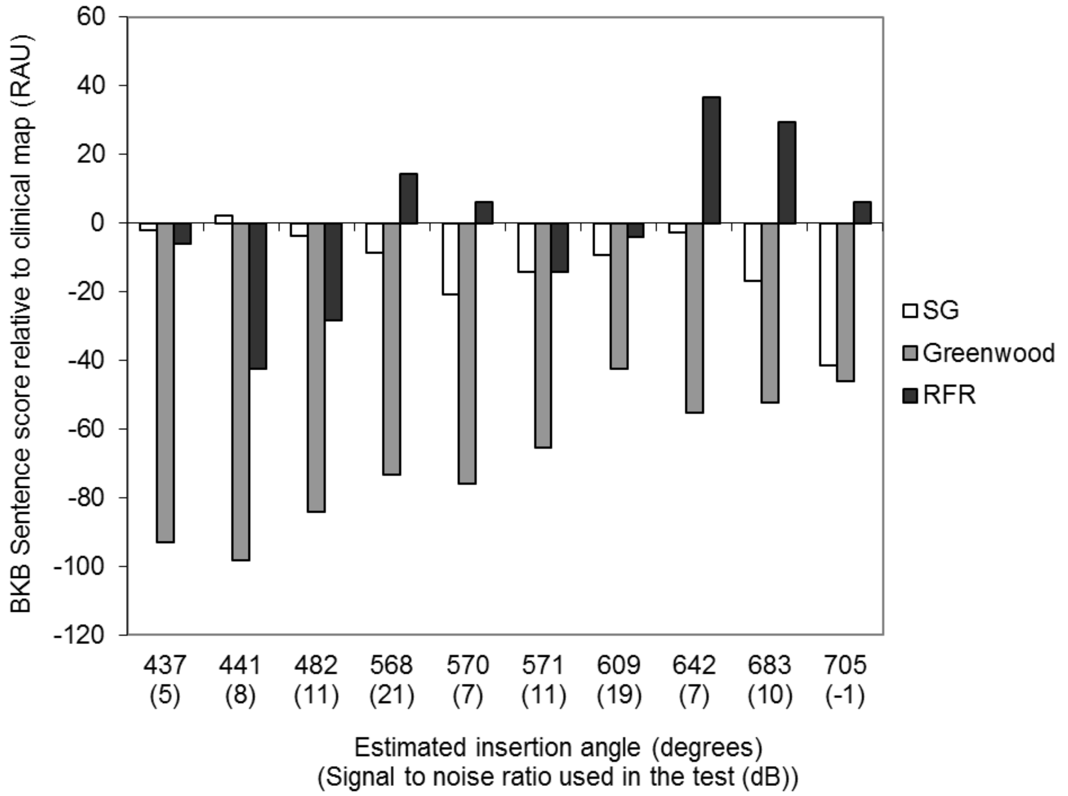


Figure 6 Individual BKB sentence scores when compared to the clinical map. The signal to noise ratio (SNR) used in each test is shown in brackets below the estimated insertion angle.

Vowel tests scores with the different maps are shown in figure 7. Test scores were normally distributed for all the different frequency allocations (Shapiro-Wilk $p>0.05$) and the condition of sphericity was met. ANCOVA was performed: the within-subjects factor was frequency allocation and the co-variate was the estimated insertion angle. A significant main effect of frequency allocation was found [$F(3,24)=15.94$, $p<0.001$]. There was also a significant interaction between the frequency allocation and the estimated insertion angle [$F(3,24)=13.62$, $p<0.001$]. There was no independent effect of estimated insertion angle [$F(1,8)=0.758$, $p=0.409$]. Post-hoc tests showed that the SG, Greenwood and RFR maps gave poorer scores than the default map [$p<0.001$, $r=0.58$ with the SG map (a large effect) and $p<0.001$, $r=0.89$ with the Greenwood map (again a large effect) and $p=0.022$, $r=0.49$ with the RFR map (a medium to large effect)]. There were no other significant differences between scores with any of the maps. A significant correlation was found between the estimated insertion angle and scores for the Greenwood allocation [$r=0.852$, $p<0.01$, 2-tailed]; participants with deeper insertion angles performed better with this allocation. No significant correlations were found between the estimated insertion angle and scores with the other frequency allocations [p=0.769 with the clinical map, p=0.108 with the SG map and p=0.477 with the RFR map].

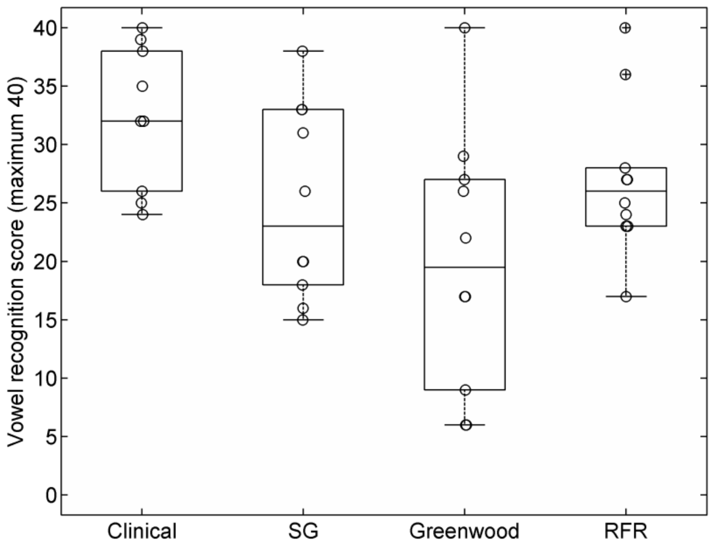


Figure 7 Vowel perception scores for the different frequency allocations. Boxes indicate the interquartile range; the solid line within each box indicates the median value. Outliers are shown by crosses. Individual data points are indicated by small circles.

Electrode discrimination results are shown in figure 8 for electrodes one to ten, which were active for all participants. The mid-way point between each pair was taken as the insertion angle of the pair. Electrode discrimination was found to be poorer for electrodes in the middle turn (insertion angle for the mid-way point of the pair > 360°), than those in the basal turn [Mann-Whitney U=574, p<0.001].

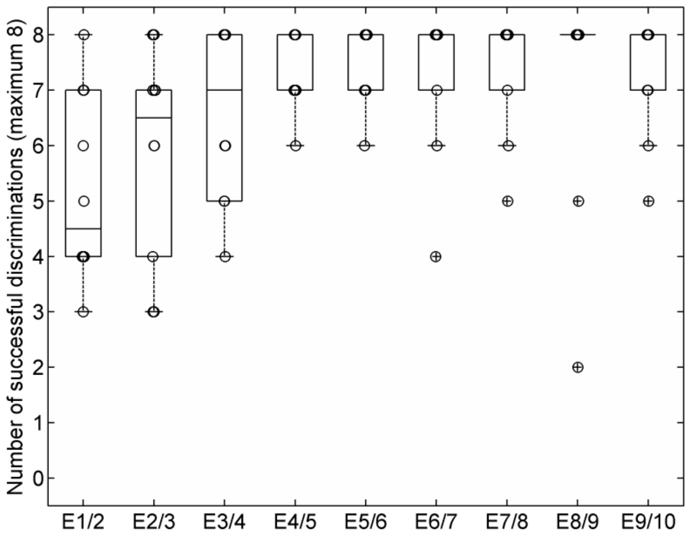


Figure 8 Electrode discrimination scores for individual electrode pairs. Boxes indicate the interquartile range; the solid line within each box indicates the median value. Outliers are shown by crosses. Individual data points are indicated by small circles.

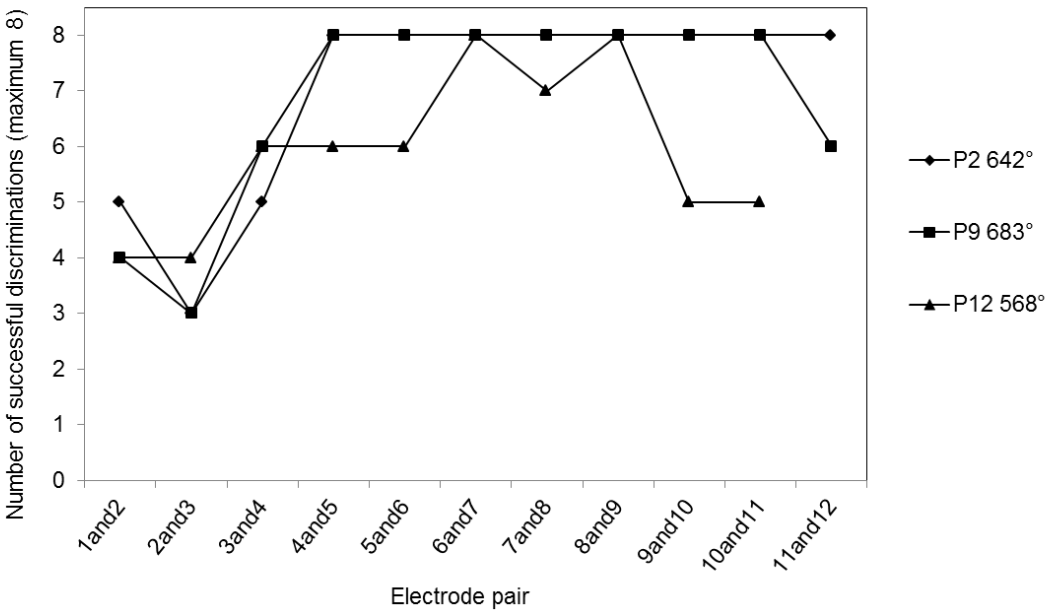
IV DISCUSSION

The present study supports the idea that speech perception by CI users is sensitive to changes of frequency allocation and therefore there is a need to optimize the frequency allocation in order to optimize performance. However, maps with frequency allocations based on the Greenwood function led to markedly reduced performance. This suggests that it does not represent the typical frequency-to-place map for CI users, or that the participants in this experiment had acclimatized to their clinical map and would have required a longer period of exposure to the map in order to acclimatize to it. Alternatively, the Greenwood function may not represent the optimal frequency mapping for CI users for other reasons. Of the three alternative maps, the Greenwood map had the greatest frequency shift from participants' clinical maps. For those with shallow insertions, there was an additional issue of a significant loss of frequency range. An interesting finding was that performance was predicted by the insertion angle for both the sentence and vowel tests with this map; those with deeper insertions (and therefore less frequency shift) performed better than those with shallow insertions. This frequency allocation also resulted in a reduction in the number of active electrodes, a reduction in the number of fine structure channels for the majority of participants and an increase in the stimulation rate. All of these factors may have contributed to the poor performance with this map, although the loss of electrodes was no greater for this map than for the SG map, for which performance was significantly better. A study by Riss *et al.* (2011) suggests that the fine structure cues have a limited effect on speech perception.

The SG map yielded poorer performance than the clinical map for the group, for vowel and sentence perception. However, the two participants with the shallowest insertions (P5 and P10), chose to continue with the SG map at the end of study, as they preferred its sound quality over that of the clinical map, whilst having similar performance with both maps. For these two participants the frequency shift from the clinical map was minimal and hence the main difference between the default and SG maps was in the relative widths of the frequency bands. The SG map has logarithmic frequency spacing whereas the default map is a fourth order polynomial function, which includes more low frequencies than the SG map for these two participants. A further difference was that the most basal electrode was deactivated in the SG map.

For both the Greenwood and SG maps, the limited time use reported by participants in the study is striking. This suggests that CI users find adjustment to a different frequency allocation a difficult step. Use of the Greenwood map was particularly limited and this suggests that CI users are not willing to use a map which results in significantly poorer performance initially, even if they have been told that it will take some time to get used to the new map.

The RFR map gave mixed results, with some participants obtaining significantly better scores on the sentence test with this map, whilst others either obtained similar or worse scores. This is an interesting finding, as all participants experienced a similar amount of frequency shift when listening to this map, when compared to their clinical map. All RFR maps were also expanded maps in comparison with the clinical maps. Three participants obtained significantly better scores on the BKB sentence test (P2, P9 and P12) with this map, using critical differences for this test, published by Martin, (1997). If the improvement was due to an improvement in the resolution of important speech sounds, it is uncertain why the benefit was only received by a minority of participants. Another possible explanation is that the reduction in frequency range assigned to the apical electrodes might have been more important for some participants than others. The reduction in frequency range was most marked for electrodes one and two. Electrode discrimination was found to be poor for some participants at the apical end of the array (figure 8). Figure 9 below shows the electrode discrimination profiles for (a) the three participants who obtained improved BKB sentence scores with the RFR map and (b) the three participants who obtained poorer BKB scores with the RFR map. Those who improved with the RFR map all demonstrated poor electrode discrimination for their apical electrodes (chance score = 2.7).



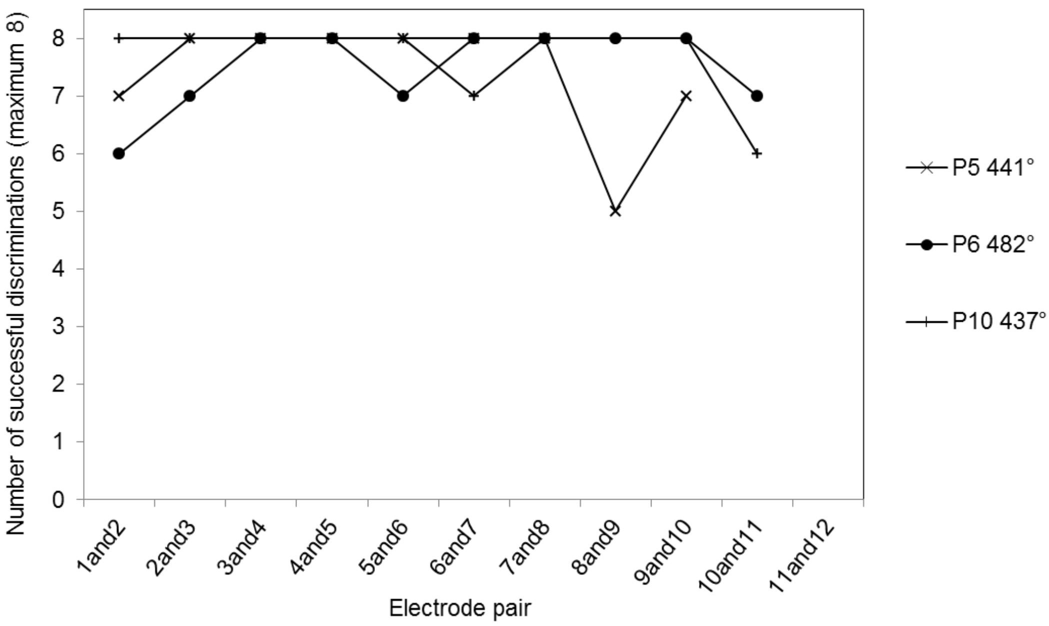


Figure 9   Electrode discrimination scores for (a) those who improved with the RFR map and (b) those who performed worse as shown by a critical difference on the BKB sentence test. The legend shows participant numbers and estimated insertion angles.

It may be that the reduced frequency range allocated to the apical electrodes in the RFR map was important in these cases, consistent with the findings of Gani *et al.*, (2007) who showed improved speech perception when apical electrodes were deactivated, in cases with deep insertions and pitch confusions at the apical end. The frequencies assigned to the most apical electrodes in the default map are of limited importance for speech intelligibility but are still present in speech-shaped noise. Another possibility is that slightly higher frequency sounds which are important for speech perception (e.g. 400 – 800 Hz) had been shifted in the basal direction to an area of the cochlea with better discrimination ability. These frequencies were assigned to electrodes three to six in the RFR map, compared to electrodes three to five in the clinical map, for those with twelve active electrodes. The majority of frequencies between 400 and 500 Hz were allocated to electrode three in the clinical map, compared to electrode four in the RFR map. However, the same frequencies were allocated to electrode five in the SG map, for which there was no improvement over the clinical map. The main difference between the SG map and the RFR map is that the SG map compresses the speech frequency range (100-8500 Hz) into nine or ten electrodes, whilst the RFR map allocates the most important speech frequencies (178-5612 Hz) to all available electrodes. Activation of the SG map resulted in deactivation of one apical electrode for participants P2 and P9, and a reduction in the frequency range assigned to the first active electrode for P2, P9 and P12. This is not dissimilar to the reduction in frequency range assigned to the apical electrodes for the RFR map for these participants. However, the compression and pitch shift associated with the SG map was less advantageous for these three CI recipients than the RFR map, which used all available electrodes.

The two participants who obtained most benefit from the RFR map both had deep insertions (682 and 642°); the third had a moderately deep insertion (568°). Conversely, the three participants who performed worse with this map all had shallow insertions (<500°). A possibility which may account for the difference in performance with this map between participants is that the basal shift associated with the map change may have been tolerated better by those with deep insertions, than those with shallow insertions.

Interestingly, whilst the RFR map offered better performance than the Greenwood map for sentence perception over the whole group, there was no statistically significant difference between those two maps for vowel perception. This may be due to the gender of the speaker, as the sentence test used a male speaker, with formants in a lower frequency range than the female speaker in the vowel test.

Alternatively, the difference may be due to the fact that the sentence test was performed in noise whilst the vowel test was performed in quiet.

The mixed results with the RFR map suggests that further work in this area would be beneficial, and that frequency allocation may need to be determined on an individual basis in order for the optimal frequency map to be obtained.

V CONCLUSIONS

Adjustment of the frequency allocation had a marked effect on speech perception for participants in this study. Mapping to the estimated normal acoustic tonotopic frequency map resulted in poor performance for all participants, whilst a compressed map limited to the area likely to contain SG cells, resulted in poorer performance than for the clinical (default) map for the majority of participants. However, performance was improved for some CI users when the frequency range of the map was reduced from 100-8500 Hz to 178-5612 Hz and logarithmic spacing of the frequency bands was introduced. These CI recipients had deep insertions and relatively poor electrode discrimination ability for apical electrodes. This study suggests that frequency allocation should be adjusted on an individual basis, and that a measure of insertion angle and/or electrode discrimination ability map help to optimize the fitting.

Appendix 2

Perception of the Pitch and Naturalness of Popular Music by Cochlear Implant Users

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Abstract

Objectives: To assess the perceived pitch and naturalness of popular music by cochlear implant (CI) users.

Methods: Eleven experienced post-lingually deafened adult CI users rated the pitch, naturalness and clarity of a popular song with ten frequency allocation settings, including the default. The alternative settings all had logarithmic frequency spacing and frequency shifts of less than one octave compared to the default map. For maps which were perceived as having incorrect pitch, participants adjusted the pitch of the song in real time using a slider, in order to normalise it, and the amount of adjustment was recorded.

Results: The default map was rated as having close to correct pitch. Naturalness rating was negatively correlated with basal shift from a baseline logarithmic map, which was the same as the default map for basal electrodes (R^2=0.77). Ratings of the clarity of the lyrics were adversely affected by basal shift. The majority of participants were able to rate and adjust pitch appropriately. The frequency shift in the map was highly correlated with participants' adjustments of the pitch slider (R^2=0.94) but the adjustments were less than expected for the majority of participants.

Discussion: The pitch ratings for the default allocation suggest that participants have acclimatised to their processors' frequency allocations. Adjustment of the pitch of the song was possible for the majority and suggested that all but one participant was experiencing frequency compression. Expansion of the frequency allocation might help to alleviate this.

Conclusion: Adjustment of the pitch of a popular song could be helpful for tuning CIs.

Introduction

Music is a highly complex sound stimulus, often combining multiple streams of acoustic information, and represents one of the greatest challenges for listening with a cochlear implant (Limb and Roy, 2014). Whilst it has been found that many CI users perceive rhythm with reasonable accuracy (Brockmeier *et al.*, 2011, McDermott, 2004, Cooper *et al.*, 2008), implant users perform much less well on tasks involving pitch and melody perception (reviews: (McDermott, 2004, Looi *et al.*, 2008, Limb and Roy, 2014), as the mechanisms for identifying the pitch of musical sounds are impaired in CI users. CI users are less able to segregate different sound sources than normal-hearing listeners (Zhu *et al.*, 2011, Galvin *et al.*, 2009) and also have difficulties with timbre perception (Kang *et al.*, 2009). Nevertheless, an increasing number of CI users actively engage with music and receive pleasure from doing so; others are frustrated with the sound quality and may engage in music-related activities less often (Philips *et al.*, 2012, van Besouw *et al.*, 2014, Drennan *et al.*, 2015).

Previous studies have reported that pitch perception for CI users is dominated by ‘place-pitch’ cues and is therefore largely dependent on the position of the electrodes in the cochlea (Plant *et al.*, 2014, Galvin *et al.*, 2007). Stimulation of the basal end of the cochlea produces a high pitch sensation and stimulation of the apical end produces a low pitch sensation, as in normal hearing. Difficulties perceiving the fundamental frequency (F0) of musical sounds arise from reduced spectral resolution (Looi *et al.*, 2008). The number of electrodes is limited in all CI systems, with a maximum of 22, compared to 3500 inner hair cells (Limb and Roy, 2014) and the spread of excitation produced by CI electrodes is broad (Cohen *et al.*, 2003), meaning that precise pitch perception is not possible. However, a minority of CI users obtain remarkably good scores on pitch perception tests (van Besouw and Grasmeder, 2011, Drennan *et al.*, 2015), showing an ability to perceive differences in pitch of less than one semitone, which is useful for melody perception. These CI users are able to perceive pitches between the centre frequencies of individual filters, making use of the fact that the filters are overlapping. This has been shown with both simultaneous and sequential stimulation (Landsberger and Galvin, 2011). Pitch perception in CI users may be assisted by weak temporal cues for low frequency sounds, which arise from harmonics processed within the same filter, as these cause amplitude modulations at the fundamental frequency. Additionally, F0 may be determined from the amplitude envelope if the stimulation rate is approximately four times the fundamental frequency or more (Looi *et al.*, 2008) and in the MED-EL Fine Structure

(FS) strategies, the stimulation rate is dependent upon the frequency of the input signal for the apical channels. This has been shown to give a lower pitch percept for some CI users for these electrodes (Simonyan, 2012). However, sometimes place-pitch and temporal pitch cues may give conflicting information (Looi *et al.*, 2008), potentially making pitch perception more difficult.

Electrode array insertion depths vary considerably: in a study of 362 Advanced Bionics CII HiFocus1 and HiRes90K HiFocus1J implants, insertion angles were found to vary between approximately 300 and 700˚, with a mean insertion angle of 480˚ (van der Marel *et al.*, 2014). A temporal bone study by (Franke-Trieger *et al.*, 2014) found that average insertion depths were greater for the 28 and 31 mm MED-EL electrode arrays, 587˚ and 673˚ respectively, with a maximum insertion of 703˚. Even for these longer electrode arrays, the array did not extend past the middle turn into the apical region, which is responsive to the lowest frequencies when sounds are presented acoustically (Greenwood, 1990). The Greenwood function relates distance along the basilar membrane to perceived pitch for normal-hearing listeners It implies that if a broad frequency range is presented to CI users with typical insertion depths, sounds will be shifted towards the base relative to the normal acoustic pitch. This suggests that CI users will receive a high pitched sensation in comparison to normal-hearing listeners (Grasmeder *et al.*, 2014). Studies have been performed in which the pitch perceived from stimulation of individual CI electrodes has been compared with sounds presented acoustically to the contralateral ear of CI users with single sided or asymmetric hearing loss, allowing the pitch percept from individual electrodes to be assessed. Some studies report that the pitch perceived for CI electrodes is similar to the acoustic pitch, at the same distance along the basilar membrane, in the contralateral ear (Vermeire *et al.*, 2008, Carlyon *et al.*, 2010). Other studies have reported pitch percepts below the Greenwood function, suggesting that the CI gives a lower pitch percept at a specific distance along the basilar membrane than acoustic pitch (Dorman *et al.*, 2007, Boëx *et al.*, 2006, Simpson *et al.*, 2009, Baumann and Nobbe, 2006).

Changes in pitch between adjacent electrodes were also found to be less than changes in pitch perceived by normal-hearing listeners for the same distance along the basilar membrane, as predicted by the Greenwood function: Zeng *et al.*, (2014), reported that the measured slope of the frequency-electrode function was only half that predicted by the Greenwood function on average; similarly Plant *et al.*, (2014) found that the slope of the electrical pitch function was shallower than expected for all except one subject; studies by (Baumann *et al.*, 2011) and (Boëx *et* *al.*, 2006) also reported smaller than expected pitch changes between adjacent electrodes for individual participants. Plant *et al.*, (2014) found that the slope of the electrical pitch function was negatively correlated with the amount of pre-operative low-frequency hearing loss in the implanted ear.

Some differences in perceived pitch may be due to differences in acclimatisation between individual CI users. CI speech processors typically map the speech frequency range to the available electrodes. A relatively small number of studies have looked at the effect of acclimatisation on pitch percept. Carlyon *et al.*, (2010) did not observe a significant effect of implant experience on perceived pitch, whereas Reiss *et al.* (2007) did observe changes in electrical pitch for implant users with a short (hybrid) electrode array. Reiss *et al.* (2015) observed different patterns of pitch perception over time in different bimodal CI users, with some individuals showing acclimatisation to the implant's frequency allocation. Other individuals showed a drop in pitch across the frequency range towards the pitch of the most apical electrode, whilst some showed no change in perceived pitch over time for any electrode. Plant *et al.*, (2014) also found variability between individuals; they observed that the pitch sensation for the most apical electrode may reduce, or may remain constant over a period of time.

Another issue to be considered in relation to the processing of music by CIs, is that the frequency range of music has energy outside of the speech frequency range and, for normal-hearing listeners, a reduction in the frequency range has been found to have an adverse effect on the perceived naturalness of music (Moore and Tan, 2003). However, a study by Roy *et al.* (2012) found that CI users rated the sound quality of musical sounds similarly, when an unfiltered signal was compared with a high-pass filtered signal with a filter cut-off of 400 Hz, suggesting that low frequency sounds contribute little to the sound quality of music for CI users. The study also suggested that CI users were insensitive to low pass filtering of musical stimuli. A study by Galvin and Fu (2011) found that melodic contour perception was better for some CI users, for bandpass filtered musical stimuli, covering the middle of the frequency range, than unfiltered stimuli and suggested that this may be due to a reduction in spectral warping, and conflicting temporal and spectral F0 cues. An alternative explanation might be that a greater number of maxima were assigned to the frequency range with the most salient cues in the middle bandpass condition than in the unfiltered condition, or that the participants who found the bandpass condition easier, might have had better neuronal survival in this area.

Appendix 2

It has been found that people with normal hearing will often have a memory of popular music at the appropriate pitch, as pop songs are commonly heard repeatedly at the same pitch and performed by the same artist (Levitin, 1994). Post-lingually deafened adults, who listened to music prior to losing their hearing, may also be able to recall the pitch of familiar pop songs and notice deviations from the normal pitch.

The purpose of the current experiment was threefold: firstly to assess the perceived naturalness and pitch of popular music for experienced cochlear implant users; secondly to assess the impact of basal shift on the perceived pitch and sound quality and thirdly to investigate the amount CI users would choose to adjust the pitch, in order to normalise it, if it was perceived as incorrect. It was hypothesised that if cochlear implant users had acclimatised to their devices, the pitch of their normal clinical maps would be perceived as essentially correct. If individual CI users had not fully acclimatised, the pitch perceived would be higher than the anticipated pitch. If a song was perceived as having inappropriate pitch, it was expected that CI users would reduce the pitch in order to correct it. Additionally, it was anticipated that for maps with an adjusted frequency allocation, producing basal shift relative to the default map, a larger adjustment to the pitch of the song would be required for the song to be perceived as correct and that there would be a correlation between the amount of frequency shift of the map and the reduction in pitch for each map. The amount of adjustment may be less than the change in frequency of the map if the electrical pitch function is compressed. Alternatively, CI users may find the task of adjusting pitch too difficult, if they are confused by conflicting temporal pitch cues.

A previous study (Grasmeder *et al.*, 2014) found that there was an approximately exponential relationship between electrode number and filter frequencies for frequency allocations mapped to the Greenwood function with the MED-EL standard electrode array. Additionally, pitch scaling experiments have shown relatively uniform changes in pitch between uniformly spaced electrodes, at least for most of the array (Boyd, 2011) . This suggests that logarithmic spacing of filter frequencies is an appropriate mapping strategy for CI users. Logarithmic spacing is also convenient for testing as adjustments made at either end of the electrode array produce uniform frequency shifts along the array. For this experiment, a range of maps with logarithmic spacing of filter frequencies were made with varying amounts of basal shift at either end of the electrode array.

Method

Participants

Thirteen unilaterally-implanted, post-lingually deafened adult cochlear implant users were recruited for the experiment. All participants had been implanted for at least one year and had MED-EL cochlear implants with either a standard or Flex28 electrode array. All participants had a full insertion of the electrode array, according to the surgeon's notes. All participants scored at least 80% correct on the BKB sentence test in quiet at their most recent annual review and were therefore considered to be good performers with their cochlear implants. One participant dropped out (P7) because he was unfamiliar with using a computer, had some other difficulties, and found the adjustment of the pitch slider, described below, too difficult to manage using a computer mouse. Another participant, P6, found that the singer's voice sounded 'hoarse' through her CI and the rough sound quality meant that she was unable to perceive the pitch of the singer's voice. She also found the experiment too difficult and dropped out. Results were obtained for the remaining eleven participants.

Details of participants' prior engagement with music were drawn from their clinical notes. It was found that music was a serious hobby for two participants: P1 learnt the piano until the age of nineteen, whilst P8 enjoyed writing songs. P9, P11 and P13 had had a limited amount of musical training at school; no data was available for P4 in relation to previous music training but music was not highlighted as an important issue in his assessment notes. The remaining participants all reported that they had enjoyed listening to music, before losing their hearing, but had not received formal music training. Further details relating to study participants at the time of testing are given in table 1.

Appendix 2

Table 1 Study participants' details

Participant	Electrode array	Processing strategy	Age (years)	Duration of implant use (years)	Gender
P1	Standard	FS4-p	62	5	Male
P2	Flex28	FS4	59	1	Female
P3	Flex28	FS4	67	1	Female
P4	Flex28	FS4	66	1	Male
P5	Standard	FSP	69	10	Female
P8	Flex28	FS4-p	28	2	Male
P9	Standard	FSP	49	8	Male
P10	Flex28	FS4	67	1	Female
P11	Standard	FS4	62	5	Female
P12	Standard	FSP	64	5	Male
P13	Standard	FS4	71	6	Female

Ethical approval for the study was obtained from the NHS National Research Ethics Service (reference 11/SC/0291). Those who participated in the experiment gave written informed consent.

Adjustment of CI frequency allocations

Ten different maps were created for each participant in the experiment, in order to compare the perceived pitch of the default map with that of other maps. The maps differed in their frequency allocation settings but no other parameters were altered. One of the study maps was each participant's own clinical map, which used the default frequency allocation in every case. This has a frequency range of 100 – 8500 Hz and allocates a larger portion of the frequency range to the apical electrodes than the basal electrodes. The alternative maps all had uniform (logarithmic) frequency spacing but different frequency ranges. The lower frequency boundaries were 225 (L0), 179 (L1) and 142 (L2) Hz and the upper frequency boundaries were 5353 (U2), 6746 (U1) and 8500 (U0) Hz, or as close to this as the processor's filter settings allowed. This meant that the frequency shift on each electrode for the centre frequency for all maps was always less than one octave, when compared to the default map. The map L0U0 had the same frequency allocation as the default map for basal electrodes, but had a different frequency allocation function shape for the apical electrodes and some associated apical shift for those electrodes, as shown in figure 1a. It was anticipated that this map would have the lowest pitch percept. The amount of basal shift was measured relative to this map. The numbers 1 and 2 for the lower and upper frequency boundaries represent shifts of one third (400 cents) and two thirds (800 cents) of an octave respectively, so the map L2U2 has a basal shift of two thirds of an octave across the whole electrode array, when compared to map L0U0. Map L0U2 has no frequency shift at the apical end but a frequency shift of two thirds of an octave at the basal end. Figure 1b shows the details of a selection of the alternative maps for all electrodes whilst figure 1c shows details of the default and U1 maps at the apical end of the array.

Appendix 2

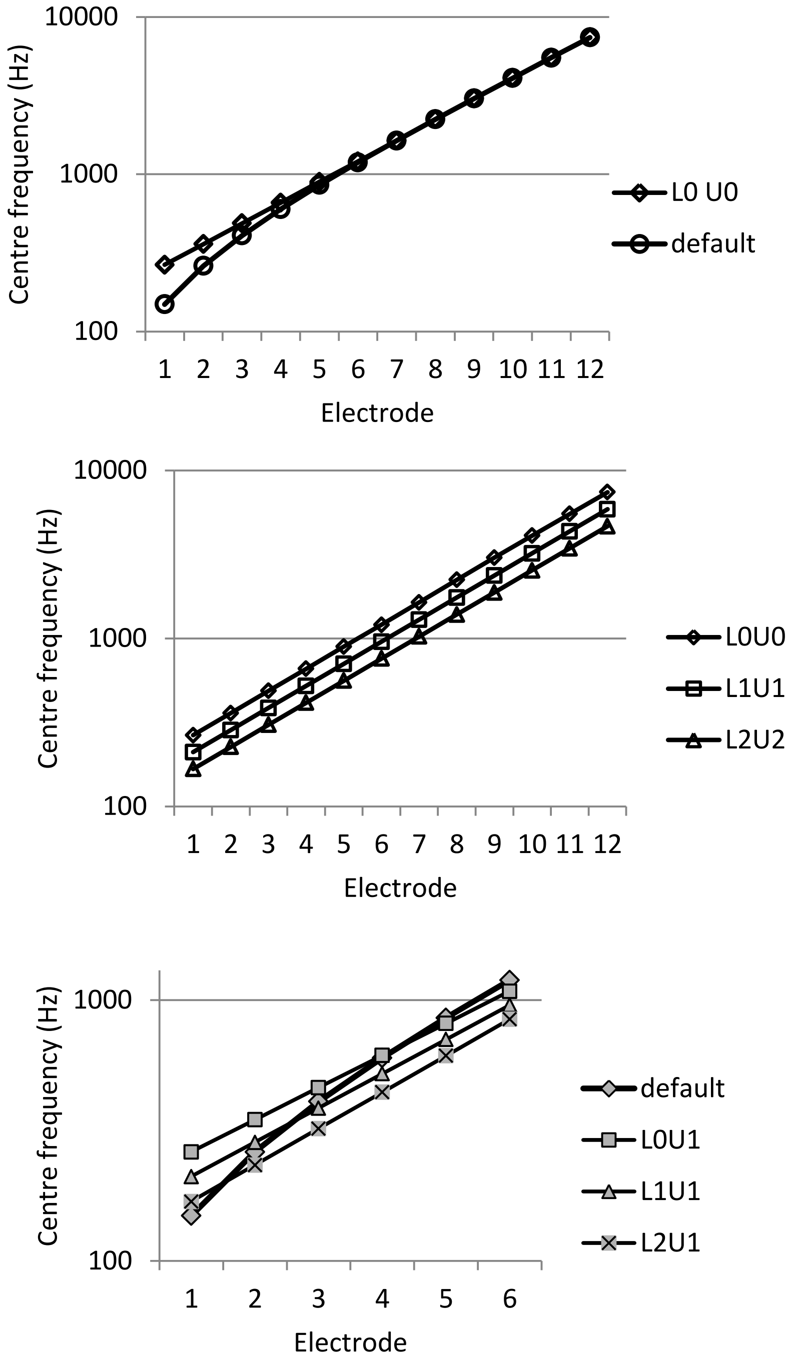


Figure 1 Frequency Allocations for study maps: (a) centre frequencies of the default and L0U0 maps for all electrodes; (b) centre frequencies of a selection of the alternative maps for all electrodes; (c) centre frequencies of the L0U1, L1U1, L2U1 and default maps for the apical half of the electrode array

For participants with the FSP strategy, some of the alternative maps had a different number of fine structure channels. The number of fine structure channels increased from one to two for P5 and from three to four for P12 for the four most basal maps; the number of fine structure channels increased from one to two for the L2 maps for P9 but decreased to zero for maps L0U0 and L0U1; an increase in the number of fine structure channels might increase the temporal cues available to these participants for these maps.

Sound Quality Ratings

Participants listened to verse 1 of a song by Sir Cliff Richard, 'We don't talk anymore' with each study map, presented in a pseudo-randomised order. This verse of the song has fundamental frequencies from 175 to 349 Hz. For the L0 maps, the fundamental frequency would therefore be attenuated for the lower notes. Temporal pitch cues may have been available for some notes, but were unlikely to be available for the highest ones, as their frequencies were above 300 Hz (Zeng, 2002). Participants were asked if they were familiar with the song and were able to answer 'Yes', 'No' or 'Not sure'. Presentation of the song was via the mixer app from the Interactive Music Awareness Programme (IMAP) (van Besouw *et al.*, 2013), which plays a video of the song, along with subtitled lyrics. Sound was routed via a sound treated box, 'Otocube', with the volume level set to 60 dB(A). A test processor (Opus2), attached to an extra-long coil cable, was used in the test box. Participants listened to a verse of the song, both the vocals and the backing tracks, and were able to watch the video too. They then rated the naturalness of the song on a visual analogue scale, which was labelled as 'Unnatural' on the left side of the paper and 'Natural' on the right side of the paper. Participants were then asked, 'Do you think that the pitch is correct?' and indicated if the pitch was correct using a visual analogue scale labelled 'Very low' on the left of the page, 'Correct pitch' in the middle, and 'Very high' on the right of the page. The backing tracks were then switched off, using the IMAP software, so that only the main vocals were heard. After listening to verse one again, participants rated the clarity of the lyrics on a visual analogue scale extending from 'Unclear' on the left of the page to 'Clear' on the right of the page.

Adjustment of Musical Pitch

The mixer app in the IMAP has a slider for the adjustment of pitch, as shown in figure 2, which allows the pitch of the song to be adjusted in real time from one octave below the normal pitch to one octave above it, using a frequency-domain pitch shifter. The pitch slider was demonstrated to participants by the tester but no information was given relating to the direction or amount to which it should be adjusted. Participants were asked to adjust the pitch of the song, to correct it, whilst listening to the same verse again, with each map. They were free to continue with just the vocals or could add in the backing tracks if they wished to do so, by pressing the icon corresponding to each instrument on the screen. An additional field was included in the IMAP software for this experiment, which shows the change of pitch in cents (from the original). This number was recorded for the pitch adjustment for each map.

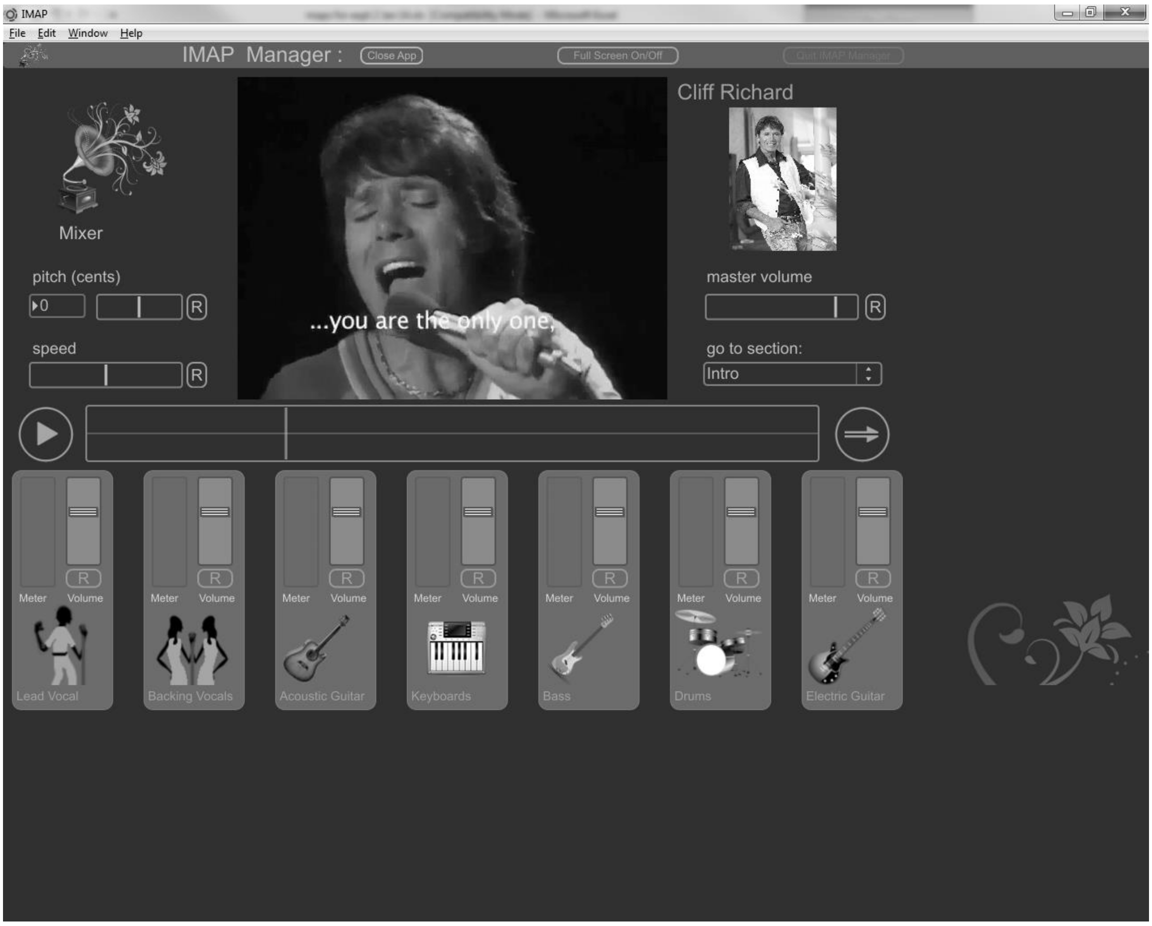


Figure 2 Graphical user interface for the mixer app in IMAP

Results

Statistical analysis

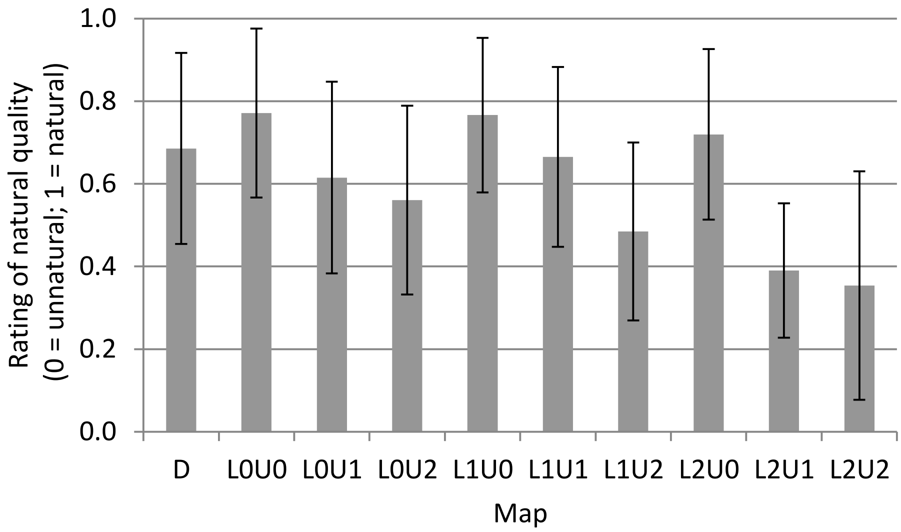
Analysis of variance (ANOVA) was used to compare different maps or conditions in cases where data were normally distributed, as indicated by a non-significant result on Shapiro-Wilk's test and Mauchly's test of sphericity gave a non-significant result. Friedman's test was used when data points were not normally distributed, unless stated otherwise. Correlations used Pearson's correlation coefficient.

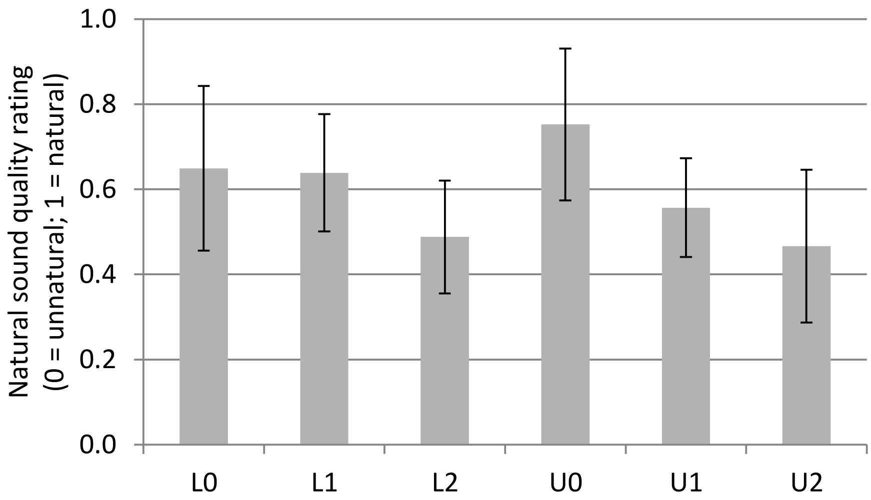
Familiarity with the Song

Participants were asked if they were familiar with Sir Cliff Richard's song, 'We don't talk anymore.' Eight participants reported being familiar with the song; participants P5, P8 and P9 reported that they were not previously familiar with it. These three participants listened to the song with their everyday map before listening with the study maps (which included the default map). None of them were found to be outliers on any of the measures described below, so their data was included in the data for the whole group (outliers were defined as being at a distance of 1.5 x inter-quartile range from the inter-quartile range or greater).

Natural sound quality for each map

Participants were asked to rate the sound quality of the music from unnatural (=0) to natural (=1), on a visual analogue scale. Ratings are shown in figure 3a.





Appendix 2

Figure 3 Participants' ratings of the extent to which the sound quality of the music was perceived as natural with different maps: (a) all maps; (b) averages across conditions: L0 = average for L0U0, L0U1 and L0U2 etc. Bars represent the mean; error bars show one standard deviation from it.

The effect of which map on the rating of natural sound quality was investigated using ANOVA. A significant main effect of map was found [$F(9,10)=7.37$, $p<0.001$]. As map L0U0 was the most apical map, and had uniform (logarithmic) frequency spacing, in common with the other alternative maps, comparisons between this map and the other maps were made. A pairwise comparison indicated that the default map did not have a significantly different rating from the L0U0 map ($p>0.05$). Pairwise comparisons (Bonferroni corrected, based on nine comparisons) suggested that the L1U2, L2U1 and L2U2 maps were significantly less natural than L0U0 ($p=0.022$, $p=0.016$ and $p=0.005$ respectively). These maps had the greatest frequency shift from the L0U0 map. To investigate the effect of frequency shift on the naturalness of the sound quality further, the amount of frequency shift was correlated with the natural quality rating, as shown in figure 4.

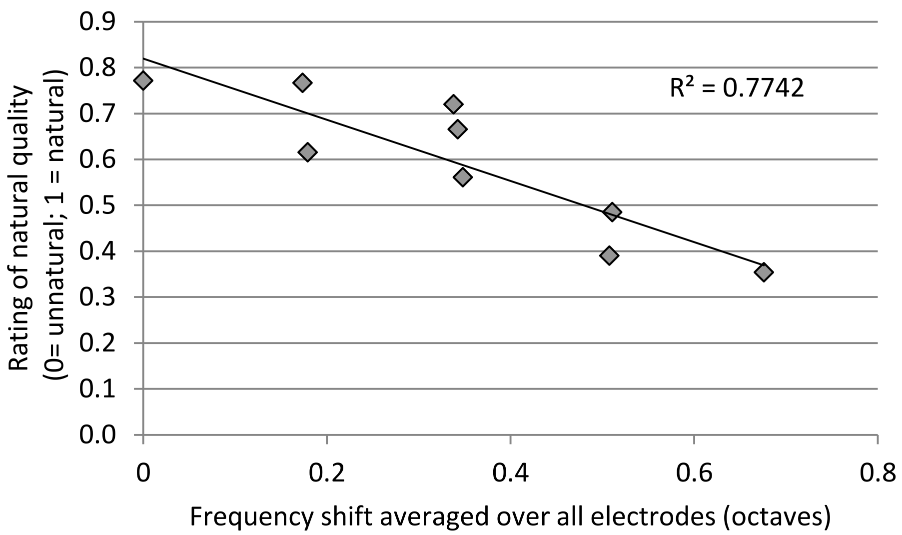


Figure 4 Correlation between the average frequency shift in the map from L0U0 and the rating of natural sound quality

A significant correlation was found between the frequency shift in the map and the rating of natural sound quality ($r=-0.881$, $p=0.002$, 2 tailed). The default map was not included in this comparison as it had non-uniform frequency spacing, unlike the other maps.

To investigate the effect of frequency shift at the apical end separately from frequency shift at the basal end, new variables were computed for each lower and upper frequency boundary setting, which were averaged over the corresponding maps (so, for example, the rating for map L0 was the average rating for maps L0U0, L0U1 and L0U2). The new variables L0, L1, L2, U0, U1 and U2 had natural sound quality ratings as shown in figure 3b.

The effect of lower frequency boundary was investigated using ANOVA. A significant main effect of lower frequency boundary was found, [$F(2,9)=7.76$, $p=0.004$]. Pairwise comparisons showed that the L0 condition was more natural than the L2 condition ($p=0.024$, with a Bonferroni correction for three comparisons applied). The L1 condition was not rated significantly different from either of the other two conditions.

Similarly, the effect of upper frequency boundary was investigated using ANOVA. A significant main effect of upper frequency boundary was found [$F(2, 9)=13.3$, $p<0.001$]. Pairwise comparisons (Bonferroni corrected for three comparisons) showed that U0 was more natural than both U1 ($p=0.025$) and U2 ($p=0.001$); U1 was not significantly different from U2 ($p>0.05$).

Judgment of Pitch

Participants were asked 'Do you think that the pitch is correct?' and rated it from very low (=-1) to very high (=1) on a visual analogue scale. To check that they had understood this task correctly, the data were examined. It was anticipated that participants would rate the majority of maps as being higher in pitch than the L0U0 map and, in particular, that the shifted maps L1U1 and L2U2 would be rated as higher in pitch than L0U0. Results for individual participants are showed that all participants appeared to have rated the maps appropriately, except for P13, who had said that the pitch was lower than expected rather than higher than expected. P13's data was therefore excluded from the analysis related to the rating of whether the pitch was correct. Ratings for the remaining participants are shown in figure 5a.

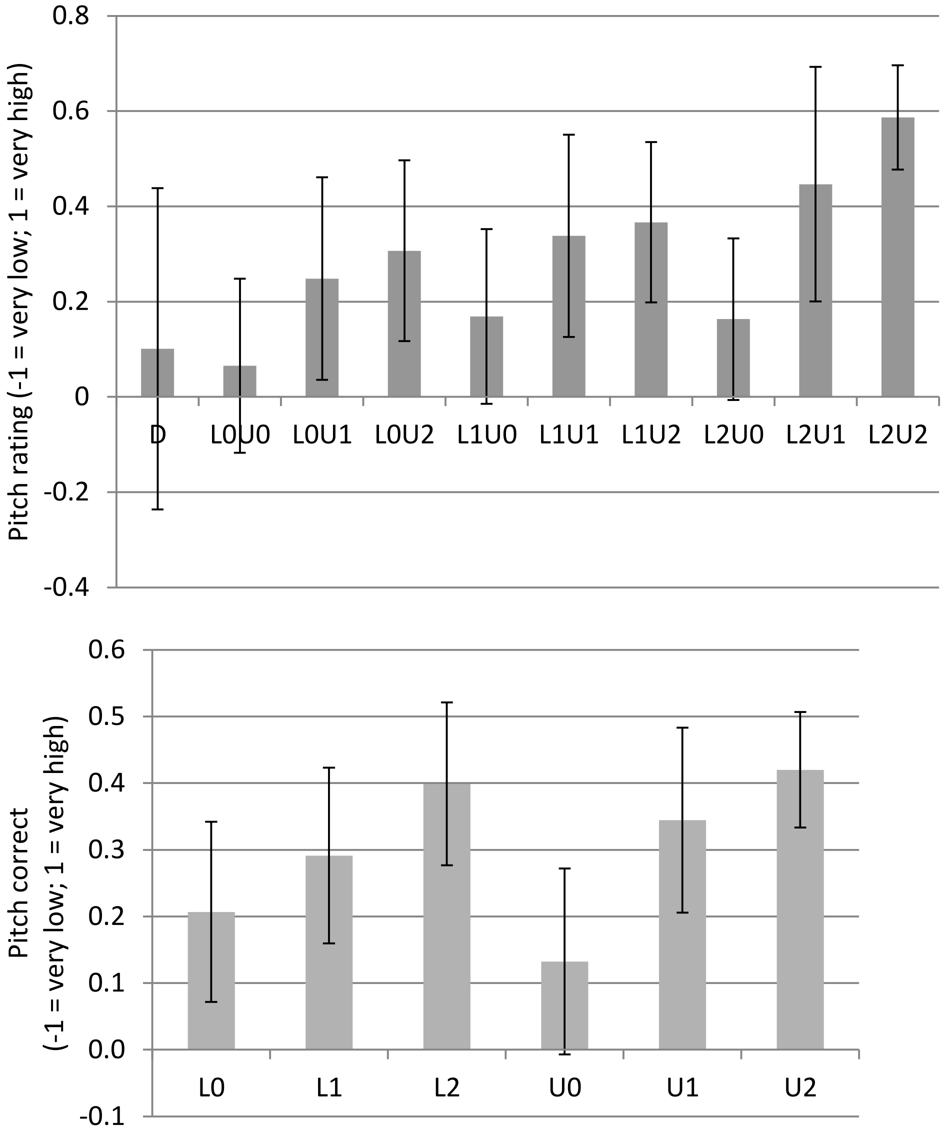


Figure 5 Pitch rating averaged over ten participants: (a) for each map; (b) averages across conditions. Bars indicate mean values and error bars show one standard deviation.

The effect of map frequency allocation on the pitch rating was investigated by ANOVA. A significant main effect of map was found [$F(9,9)=6.69$, $p<0.001$]. Pairwise comparisons showed that there was no significant difference in pitch rating between the default and L0U0 conditions. When compared with the L0U0 condition, with Bonferroni corrections for nine comparisons applied, it was found that maps L0U2, L1U2 and L2U2 were rated as significantly higher in pitch than the L0U0 condition ($p=0.045$, $p=0.01$ and $p<0.001$ respectively). In addition, a significant correlation was found between the frequency shift from the L0U0 map and the average rating of pitch across the ten participants included in the analysis

(r=0.924, p<0.001, 2 tailed), as shown in figure 6. The default map was excluded from this analysis on account of its non-uniform frequency spacing.

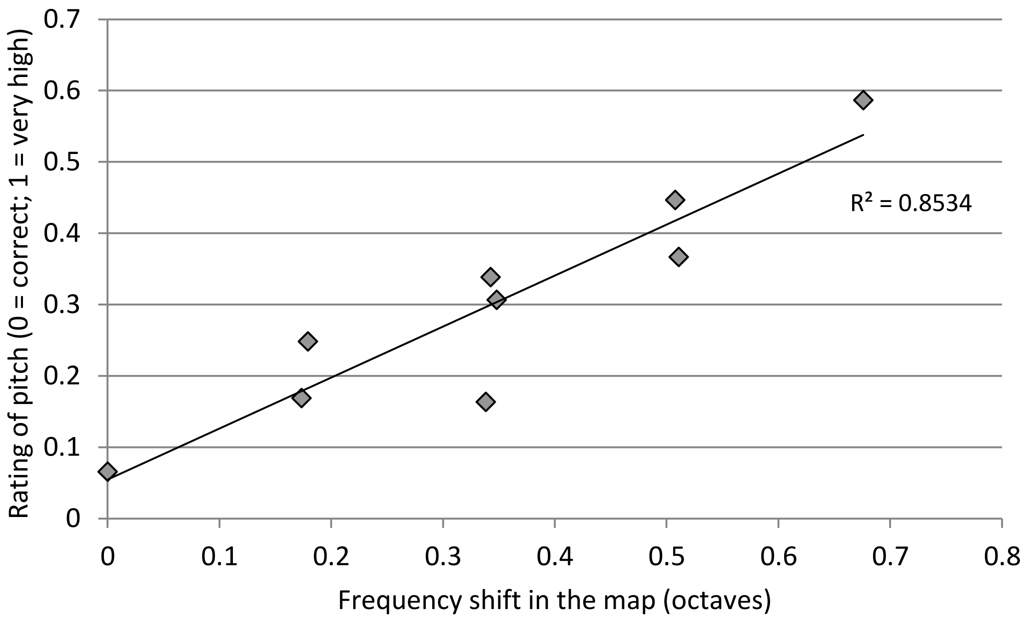


Figure 6 Frequency shift in the map and rating of pitch, averaged over ten participants

To investigate the effect of the lower and upper boundaries separately, new variables were computed: the average pitch rating for each of the conditions L0, L1, L2, U0, U1 and U2 was computed from the corresponding maps for these ten participants. Ratings for these new variables are shown in figure 5b.

The effect of lower frequency boundary was analysed using ANOVA. A significant main effect of lower frequency boundary was found [$F(2, 9)$=7.42, p=0.004]. Pairwise comparisons, with a Bonferroni correction for 3 comparisons, showed that the L2 condition was rated as significantly higher in pitch than the L0 condition (p=0.019). The L1 condition was not rated significantly differently from either of the other two conditions (p>0.05).

The upper frequency boundary was also analysed using ANOVA. A significant main effect of upper frequency boundary was found [$F(2,9)$=21.5, p<0.001]. Pairwise comparisons, with a Bonferroni correction for 3 comparisons, showed that the U1 and U2 conditions were rated as significantly higher in pitch than the U0 condition (p=0.013 and p<0.001, respectively) but the difference between the U1 and U2 conditions was not significant (p>0.05).

Clarity of the Lyrics

Appendix 2

Participants were asked if the lyrics were clear and rated the lyrics between unclear (=0) and clear (=1), on a visual analogue scale. Ratings for the clarity of the lyrics were not found to be normally distributed for the default, L0U1, L0U2 and L1U1 maps. Ratings are shown in figure 7.

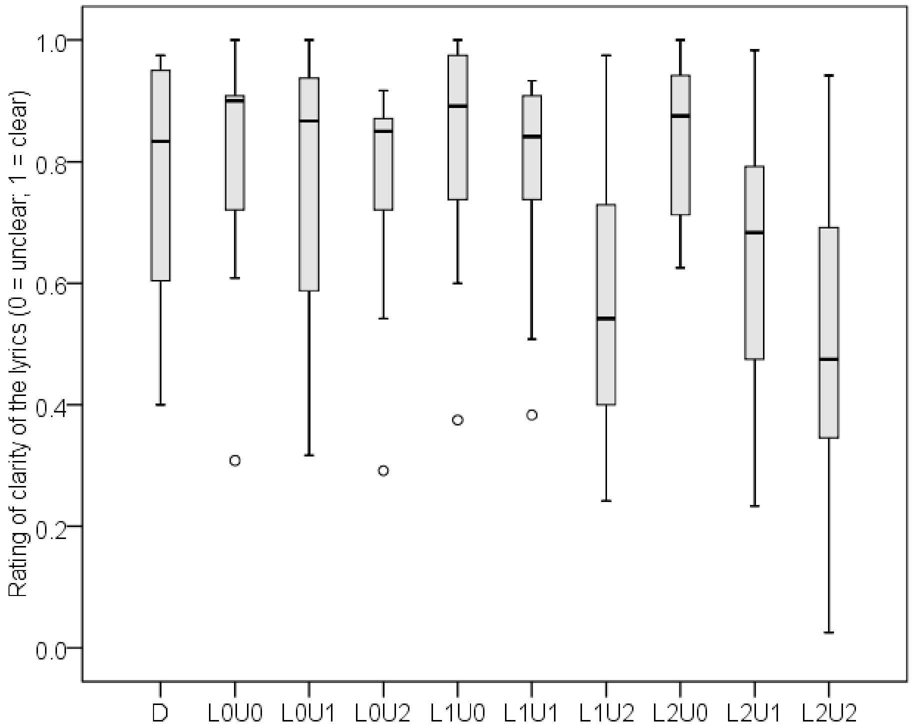


Figure 7 Participants' ratings of the clarity of the lyrics for all maps. Boxes represent the inter-quartile range and the median is shown by a thick horizontal line. Outliers are represented by small circles.

Friedman's test was used to investigate the effect of map on the clarity of the lyrics. A significant effect of map was found [Chi-square(9)=25.0, p=0.003]. No significant difference was found between the clarity of the lyrics for the default and L0U0 maps, when tested with Wilcoxon's signed ranks test (Z=-0.267, p>0.05). The remaining maps were compared with the L0U0 map: in this case Bonferroni corrections for nine comparisons were not applied, as this contradicted the result of Friedman's test. Wilcoxon's signed ranks test suggested that the lyrics of the L1U2 and L2U2 maps were less clear than those of the L0U0 map (Z=-2.09, p=0.037 for L1U2 and Z=-2.536, p=0.011 for the L2U2 map).

Adjustment of Pitch

Participants were asked to adjust the pitch using the slider to correct it, for those maps for which they had rated it as incorrect. It was anticipated that participants would reduce the pitch of the song for the majority of maps, and specifically the maps L1U1 and L2U2 would be adjusted downwards relative to map L0U0, if participants had understood the task correctly. From examination of the data, it was found that all participants, except P3, had adjusted the pitch slider appropriately. P3 appeared to find this task difficult, at first, and moved the pitch slider in the wrong direction for three out of four maps in her first session. The results from her second session are much more similar to those for other participants and to her data for the rating of pitch. However, in view of the inconsistency, P3's results were excluded from this part of the data analysis, leaving data for ten participants, as shown in figure 8. It was found that the data for the default and L1U2 maps was not normally distributed (Shapiro-Wilk<0.05).

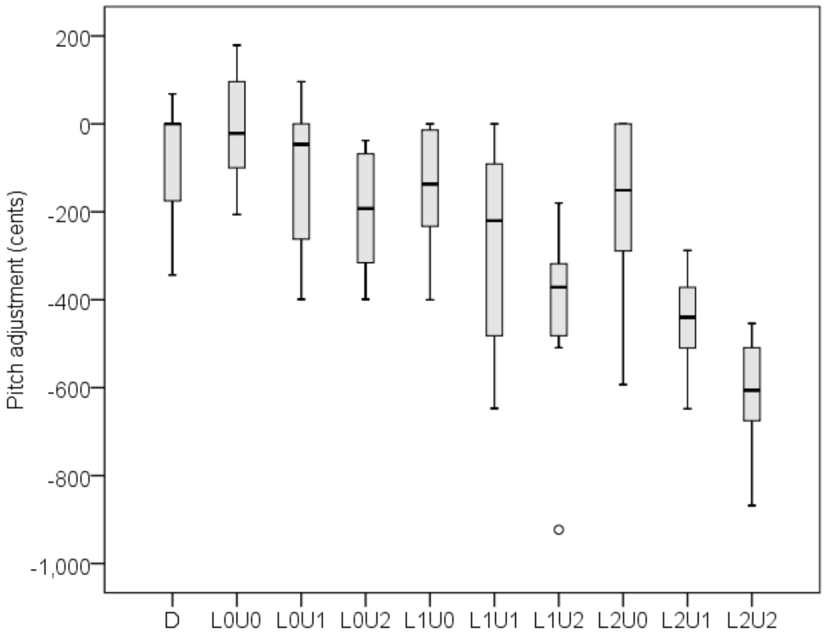


Figure 8 Pitch adjustment for different maps for ten participants. Boxes represent the inter-quartile range and the median is shown by a thick horizontal line. An outlier is shown as a small circle.

For the L1U2 map, the lack of normality appeared to be due to an outlier (P1). The default and L1U2 map was compared to the L0U0 map using Wilcoxon's signed ranks test, in view of this finding. The default map was not significantly different from the L0U0 map (Z=-0.770, p>0.05). The remaining maps were compared using ANOVA, as the conditions were met for all but the L1U2 map. A significant main effect of map was found [$F(8,9)=20.8$, $p<0.001$]. Pairwise comparisons, with a Bonferroni correction for eight comparisons applied, showed that the pitch adjustment for maps L0U2, L1U1, L1U2, L2U1 and L2U2 was significantly greater than that for map L0U0 (*p*=0.011, *p*=0.031, *p*=0.001, *p*<0.001 and *p*<0.001) respectively.

When the frequency shift in the map was compared with the average pitch adjustment for each map in cents (with the default map excluded), a very strong correlation was observed (*r*=-0.968, *p*<0.001, 2 tailed), as shown in figure 11. However, it was found that the magnitude of the pitch adjustment was smaller than the frequency shift in the map.

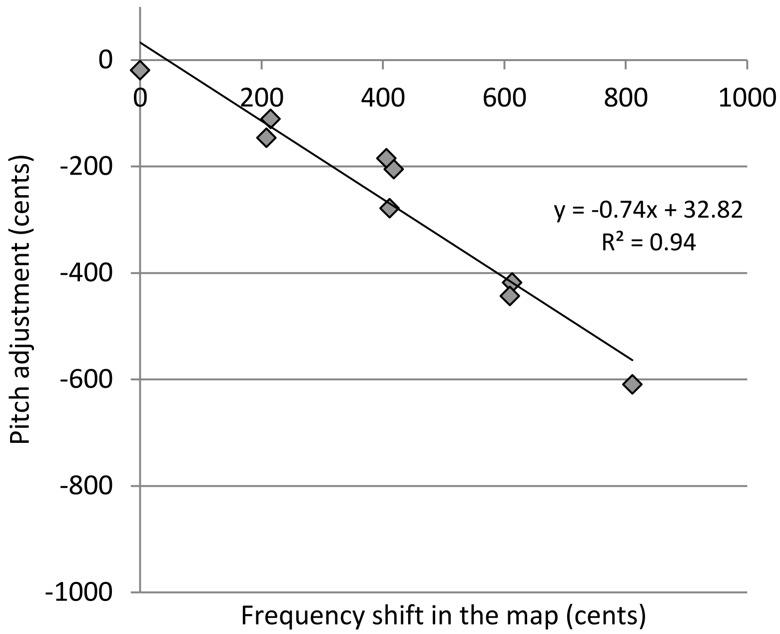


Figure 9 Frequency shift in the map compared with the pitch adjustment averaged across ten participants

Summary of Results:

Main findings:

The naturalness of the sound quality of music was found to be affected by frequency shifts within the participants' maps for these CI users: as the frequency shift increased, the music was rated as sounding less natural.

Post-lingually deafened adults were able to rate pitch as being too high or too low appropriately in most cases, when their maps were adjusted. Similarly, the majority of participants were able to correct pitch in the appropriate direction in response to the frequency shift in the map.

The default allocation was rated as having close to correct pitch on average (rated as 0.1 on a scale from 0 to 1) and the median pitch adjustment for the default map was zero.

Naturalness of the sound quality appeared to be influenced more by electrodes four to six than electrodes one to three, as indicated by the fact that L0 is rated as similar to the default map but more natural than L2.

For the majority of maps, the lyrics were found to be reasonably clear (median rating >0.8 for 7 out of 10 maps). For the maps with greatest basal shift, the lyrics were reported as less clear.

There was a very strong correlation between the frequency shift in the map and the average pitch adjustment made (r=-0.968). This was higher than for the rating of 'pitch correct'.

The amount of adjustment was less than expected: around 0.75 of the amount of frequency shift.

Discussion

Rating of Naturalness

Adjustment of both the upper and lower frequency boundaries affected the rating of natural sound quality, as shown in figure 3b. Additionally, the rating was correlated with the amount of frequency shift of the map, when compared to the L0U0 condition, with an R squared value of 0.77 (figure 4). This suggests that the perceived pitch accounted for a large part of the variance in relation to the natural sound quality rating.

For the upper frequency boundary, basal shift was accompanied by a reduction in the frequency range, whereas for the lower frequency boundary, basal shift was accompanied by an increase in the frequency range. The results for natural sound quality rating indicate that participants were unconcerned about the loss of frequency range at the apical end for the L0 maps: L0U0 was rated as having similar naturalness to the default map, even though sounds from 100 to 224 Hz were not included in the map. The lowest notes in the song (F3 to A3) had F0 less than 225 Hz, and would have been attenuated by the L0 maps. It maybe that the lower notes within the song did not greatly influence the naturalness rating but there is also the possibility that the rating of naturalness was not dependent on F0.

Appendix 2

It is likely that participants' attention would have been drawn to the channels with the highest amplitudes when listening to the song. Spectral analysis of individual notes, as shown in figure 10, shows that the higher harmonics had greater amplitude than F0, by as much as 20 dB. The third octave bands with the highest amplitudes had centre frequencies of 630, 1000, 1250 and 2500 Hz for the note E3 (330 Hz), corresponding to the second, third, fourth and eighth harmonics.

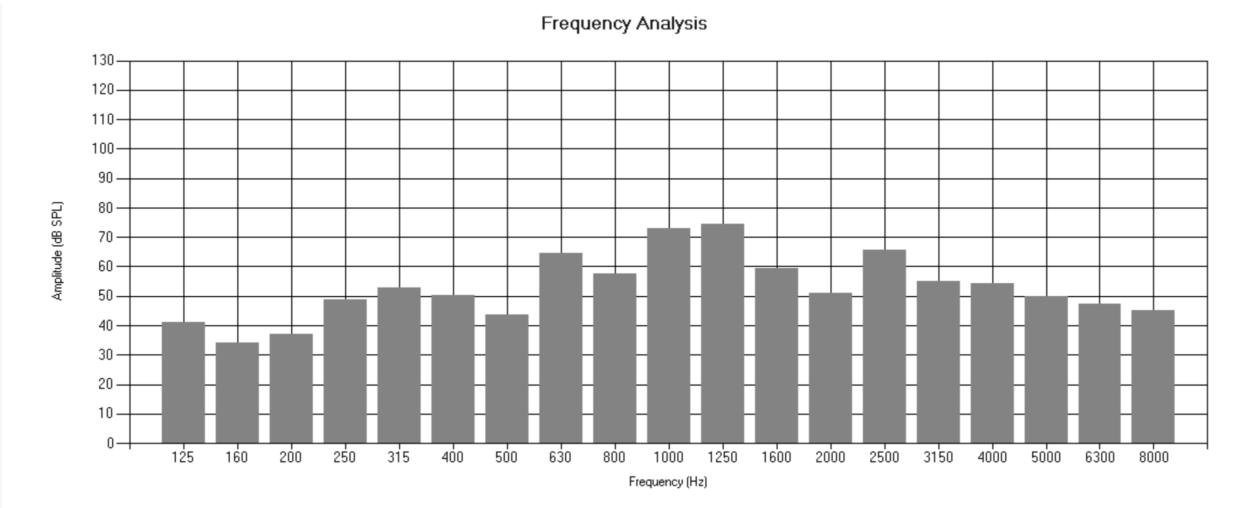


Figure 10 Spectral analysis of E4, 330 Hz, for the word 'one', towards the end of verse 1. Bars represent the amplitude of the signal within each third octave band from 125 to 8000 Hz.

Participants rated the L2 maps as less natural than the L0 maps. This suggests that electrodes four to six were more influential in the rating than electrodes one to three, as the default frequency allocation is closer to the L0 maps for electrodes four to six, corresponding to frequencies of 500 Hz to 1000 Hz approximately, and closer to the L2 maps for electrodes one to three, corresponding to frequencies less than 500 Hz approximately. This is consistent with the spectral analysis above, suggesting that the mid frequencies were more important than the low frequency F0, for rating naturalness for this song. A comparison of the maps is shown in figure 1c.

Participants' abilities to perform pitch-related tasks

Nine out of the twelve participants who attempted the experiment were able to perform both of the pitch-related assessments and eleven of them were able to perform one of the assessments. P6, who was unable to perform either assessment, is known to have problems with electrode discrimination for approximately half of the adjacent electrode pairs on her electrode array. This suggests that these tasks may require a minimum level of pitch discrimination ability. P12 had difficulty with the pitch rating task: she described the maps with the greatest basal shift as being low pitched rather than high pitched. Similarly, P3 appeared to have difficulty with pitch direction when she attempted the pitch adjustment task in her first session. For three maps, for which she had correctly identified as sounding high pitched for the pitch rating, she adjusted the pitch upwards rather than downwards. P3 realised that she found this task difficult and commented that a person with more musical training might find it easier. However, the correlation between the frequency shift in the map and the pitch adjustment was extremely high for the remainder of the group: R-squared = 0.94. This was greater than for the correlation between frequency shift and pitch rating (R-squared = 0.85) and had the additional benefit that the amount of pitch shift could be measured. This was achieved in spite of the fact that the majority of participants had limited or no musical training and three of them were not previously familiar with the song.

Perception of the pitch of the song with the default map

The default map was rated as having close to correct pitch, on average, by the group. The average pitch adjustment was less than one semitone (71 cents), in the downwards direction. This suggests that the majority of participants have acclimatised to their CIs. Had the Greenwood map been appropriate for experienced CI users, or even the spiral ganglion map described by Stahkovskaya (Stakhovskaya *et al.*, 2007), it is likely that participants would have made much larger adjustments to the pitch of the song in order to correct the pitch of the default map. Insertion angles for P1, P11, P12 and P13 were estimated from post-operative X-rays for a previous experiment (Grasmeder *et al.*, 2014) and were found to be between 570 and 680˚, consistent with insertion angle measurements for the MED-EL standard electrode array reported elsewhere (Radeloff *et al.*, 2008). In order to map their cochlear implants to the Greenwood function, large apical shifts were required (0.5 – 0.9 octaves on electrode 6). Even larger apical shifts may have been required to map the frequency allocation to the Greenwood function for some of the other participants in this experiment, as they had shorter electrode arrays (Flex28), which give shallower insertion angles on average. It is highly unlikely that the participants in this experiment would perceive the Greenwood map as having normal pitch, as they rated the default map as sounding correct, even though it is shifted in the basal direction by half an octave or more from the Greenwood map. The findings from this experiment are more consistent with the findings of (Plant *et al.*, 2014), suggesting acclimatisation to the implant's frequency allocation or to the pitch of the most apical electrode in the majority of cases.

Perception of the pitch of the song with the alternative maps

For the alternative maps with basal shift, the place-pitch cue would have produced a high-pitch sensation whilst any temporal pitch cues would have suggested that the pitch was unchanged, as the song was presented at the same pitch each time participants were asked to rate the naturalness and pitch of the song. A conflict between the place-pitch and temporal pitch cues would have been present for the maps with basal shift. When the pitch of the song was adjusted using the slider, this discrepancy would have been maintained at the same level. The majority of participants were able to rate the pitch in line with the place-pitch cue and make the pitch adjustment, in spite of this potential confusion.

Pitch adjustment

The correlation between the frequency shift in the map and the pitch adjustment is remarkably high over the group (r=0.968). However, the gradient of the regression line is -0.74, indicating that participants adjusted the pitch of the song by a smaller amount than the frequency shift in the map. This finding is consistent with the frequency compression reported in pitch matching studies (Baumann *et al.*, 2011, Boëx *et al.*, 2006, Zeng *et al.*, 2014, Plant *et al.*, 2014). The amount of compression was found to vary between individuals: only P1 had the expected one-to-one relationship between frequency shift and pitch adjustment of the song. For the remaining nine participants who were able to manage the pitch adjustment task, the regression line had a slope between -0.48 and -0.8. This suggests that expansion of the frequency allocation could be helpful, assuming that the corresponding reduction in frequency range is not large enough to have a negative impact on the sound quality. However, this should be implemented at the time of fitting, ideally, given the fact that acclimatisation to the new allocation would need to take place. Another potential method of reducing frequency compression is deeper insertion of the electrode array.

Implications for mapping

The majority of participants in this study were able to make an adjustment to the pitch of a song appropriately, in response to a change of frequency allocation. The adjustment took only a short amount of time and required only a computer and soundfield or Otocube system. Assessments of this nature could be helpful for tuning cochlear implants, in that they represent everyday sounds, and allow aspects of sound perception to be investigated, which are often overlooked in traditional tuning methods. In particular, individuals with frequency compression could be identified and expansion of the frequency allocation could be applied to compensate for this.

Appendix 3

Table 17 Lower frequency boundaries for all participants for the Greenwood map

	Electrode	lower frequency boundaries										
Participant	1	2	3	4	5	6	7	8	9	10	11	12
P2	197	316	485	744	1107	1542	2163	3126	4579	6712	off	off
P3	299	442	643	962	1395	1884	2642	3681	5217	7428	off	off
P5	581	828	1196	1679	2302	3108	4251	5804	8263	off	off	off
P6	449	650	972	1408	1903	2664	3708	5246	7468	off	off	off
P7	240	370	554	839	1233	1683	2373	3360	4864	6987	off	off
P8	133	232	378	599	920	1305	1813	2726	4084	6222	off	off
P9	152	259	412	643	981	1385	1930	2862	4254	6392	off	off
P10	608	833	1140	1591	2226	2953	3856	5090	6635	off	off	off
P11	297	440	639	957	1389	1875	2633	3669	5205	7410	off	off
P12	302	446	647	967	1403	1895	2654	3697	5233	7450	off	off

Table 18 Lower frequency boundaries for all participants for the SG map

	Electrode	lower frequency boundaries									
Participant	1	2	3	4	5	6	7	8	9	10	11	12
P2	off	100	134	224	366	557	865	1415	2391	4098	off	off
P3	100	120	187	307	490	721	1128	1768	2870	4735	off	off
P5	166	255	403	622	939	1404	2156	3335	5516	off	off	off
P6	122	190	311	496	731	1140	1786	2892	4772	off	off	off
P7	off	100	156	259	419	623	978	1561	2601	4339	off	off
P8	off	off	100	172	290	450	686	1176	2040	3680	7956	off
P9	off	100	110	187	315	485	745	1256	2158	3823	8201	off
P10	175	257	380	580	898	1310	1884	2772	4031	6687	off	off
P11	100	119	186	305	487	717	1122	1760	2860	4719	off	off
P12	100	121	189	309	493	727	1135	1778	2882	4756	off	off

Appendix 4

Map Quality Questionnaire version 1 5/4/2011

Participant Number:

Date: Session:

Your new map has been saved in programme ….. of your processor. You may notice that it sounds similar to your normal map or it may sound quite different.

Please use the new map as much as you feel able to over the next few weeks and compare it with your everyday map in programme …… It may take some time to get used to the new map (at least a few days), so please do give it a good try. If you find the sound quality unacceptable, however, do feel free to return to your everyday map.

In about 6 weeks time you will be asked to return to the clinic for another appointment. Please complete the two questions below prior to your appointment:

How often have you used the new map?

☐	☐	☐	☐	☐
Very little	Less than half the time	About half the time	More than half the time	All the time

How do you rate the sound quality of the new map?

Please place a mark on the line between the two extremes to indicate how you find the new map.

Very poor |——————————————————| Very good

Thank you for completing this questionnaire.

Appendix 5

Calibration of the Piano Test

The calibration setup for piano stimuli is shown in figure 7.4. Sounds were presented to the processor from a loudspeaker in a sound treated room, as used in the test. The processor was placed on the pinna of a manikin (KEMAR) and the output from the front end of the processor was taken via a custom made lead to the line-in on a computer. An initial adjustment was made following measurements on a single processor of each type. The output of 3 processors of the same type was then measured for each sound stimulus. The Average RMS power in dB was recorded in Adobe Audition for a fixed time window (of 1.2 s) containing the stimulus. Following this further adjustments to the sound levels and measurements were made as necessary.

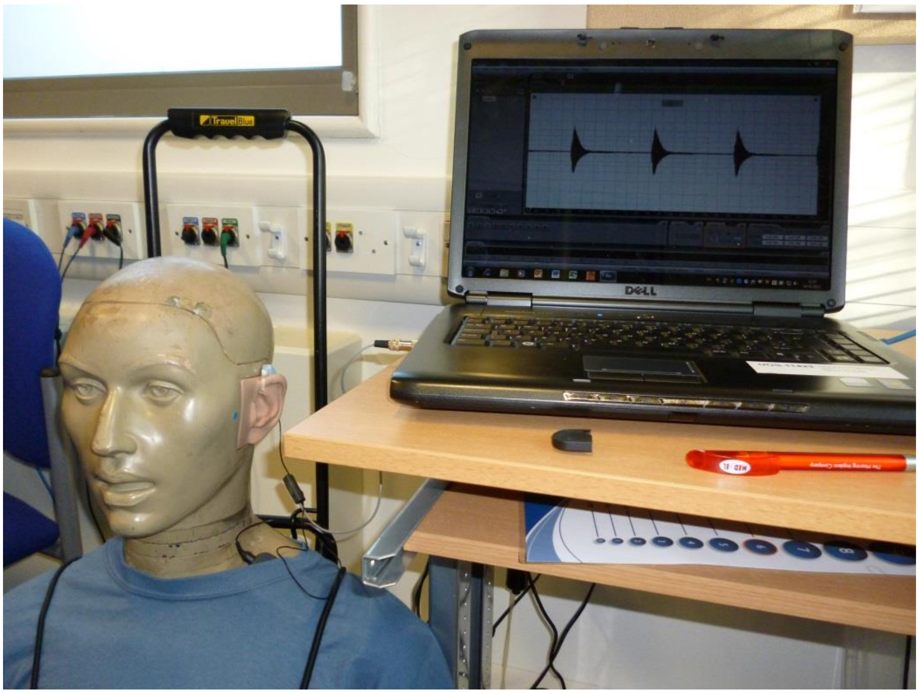


Figure 94 Calibration setup for the Piano Pitch Discrimination Test

Measurements of Average RMS Power for each level of the test were measured with 3 processors as shown in Table 19.

Table 19 Measurements of Average RMS power for Opus 2 processors with Piano Stimuli

Distance above the reference frequency (cents)	Reference stimulus RMS power – target stimulus RMS power (dB)		
	Processor 1	Processor 2	Processor 3
1600	-1.6	-1.1	0.9
800	-0.8	1.4	-0.5
400	1.0	0.6	0.5
200	0.2	-1.8	-0.6
100	-1.3	-1.5	1.4
64	0.5	3.0	1.3
32	-2.8	-2.9	-2.2
16	0.7	0.1	-1.5
8	-0.7	0.1	0.2
4	-1.3	0.6	-0.4
2	-1.4	-1.6	-1.5
1	0.4	-2.7	-2.0

As piano stimuli are time-varying in nature, the calibration was more difficult for these stimuli than for the pure tone stimuli used for the electrode discrimination test described in section 7.5. However, stimuli were successfully adjusted to within ± 3 dB of the level of the reference stimulus. Following the above measurements, the following further adjustments were made to try to reduce the difference in level between the reference and target stimuli: the level of the 64 cents file was increased by 1 dB; the level of the 32 cents file was reduced by 2 dB and the level of the 1 cent file was reduced by 1 dB.

This procedure ensured that sounds were of approximately equal loudness having been processed by the front end of the processor but there is also a frequency shaping filter which occurs after the front end. In order to correct for this, the inverse of the implant's frequency shaping filter was applied to the sound stimuli after they were calibrated as detailed above.

Appendix 6

Music Quality Rating

Map:

You are going to hear part of Sir Cliff Richard's song 'We don't talk any more'.

Are you familiar with this song?

Yes ☐ No ☐ Not sure ☐

Please listen to the song and think about how natural it sounds with the map which you are currently using. When it has finished, please indicate on the line below how natural you think it sounds.

Unnatural Natural

Do you think that the pitch is correct? Please indicate how low or high you think it is on the line below.

Very low Correct pitch Very high

You are now going to hear verse one again. Please focus on the lyrics (words) and think about how clear they are. When the verse has finished, please indicate on the line below how clear you think the lyrics are.

Unclear Clear

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