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

Mary L Grasmeder[a)], Carl A Verschuur

Auditory Implant Service, ISVR Building 19, University of Southampton, Southampton SO17 1BJ United Kingdom

Vincent B Batty

Wessex Neurological Center, University Hospital Southampton NHS Foundation Trust, Tremona Rd, Southampton SO16 6YD United Kingdom

[a)]Author to whom correspondence should be addressed. Electronic mail: M.L.Grasmeder@soton.ac.uk

7 February 2014

Cochlear implant frequency allocation

Keywords: cochlear implant, tuning, pitch, frequency

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 spiral ganglion 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.

PACS number: 43.71.Ky

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.

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; a; b; Başkent and Shannon, 2003; 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 spiral ganglion cells are likely to be the means by which the auditory nerve is accessed for CI users. Spiral ganglion cells are arranged over a shorter distance along the length of the cochlea than hair cells (Kawano *et al.*, 1996; Sridhar *et al.*, 2006; Stakhovskaya *et al.*, 2007). The function relating frequency matched points along the organ of Corti and spiral ganglion 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 spiral ganglion and x = % distance from the base for the organ of Corti.

The function reflects the curvature of the cochlea such that the equation maps from the angle of rotation for the organ of Corti to the angle of rotation for the spiral ganglion very closely, as given in Stakhovskaya *et al.* (2007), figure 9. Whilst the Greenwood function suggests that pitch changes uniformly with length along the organ of Corti over approximately 90% of its length, equation two suggests that pitch changes relatively uniformly with length along approximately 80% of the spiral ganglion and thereafter pitch decreases more rapidly towards its apical end. A frequency-matched map for the spiral ganglion 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 (Baumann and Nobbe, 2006; Boëx *et al.*, 2006; Dorman *et al.*, 2007; Di Nardo *et al.*, 2008; Vermeire *et al.*, 2008; Simpson *et al.*, 2009; Carlyon *et al.*, 2010; Di Nardo *et al.*, 2010; Baumann *et al.*, 2011). 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 organ of Corti (Greenwood function) nor the spiral ganglion (Stakhovskaya *et al.*, 2007) and may be related to a loss of spiral ganglion 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 (Skinner *et al.*, 2007; Finley *et al.*, 2008). 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 organ of Corti (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, (Nelson *et al.*, 1995; Gani *et al.*, 2007; Boyd, 2011) 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 (Fu and Shannon, 2002; McKay and Henshall, 2002;

Goupell *et al.*, 2008; Li *et al.*, 2009; Sagi *et al.*, 2010, 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 spiral ganglion 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 spiral ganglion 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 here

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.

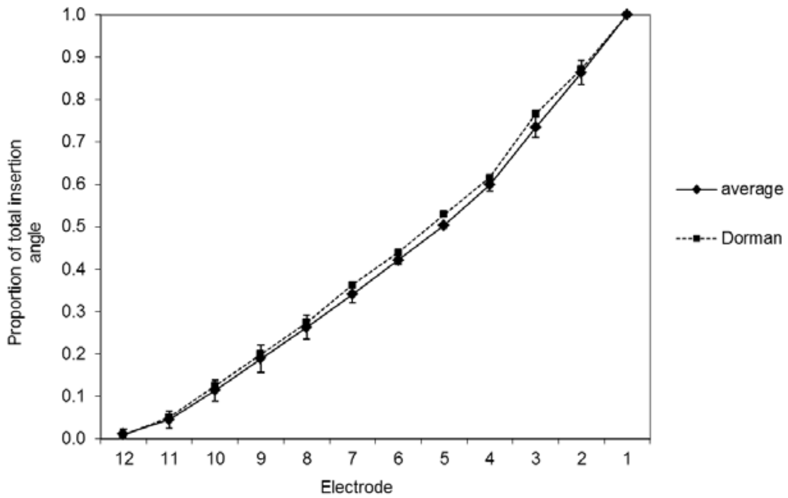


Figure 1 Mean insertion angles as a proportion of the total insertion angle (measured from the round window) for electrodes for five X-rays included in the review and those for the recipient in Dorman *et al*. (2007). Error bars = 1 standard deviation.

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 here.

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.

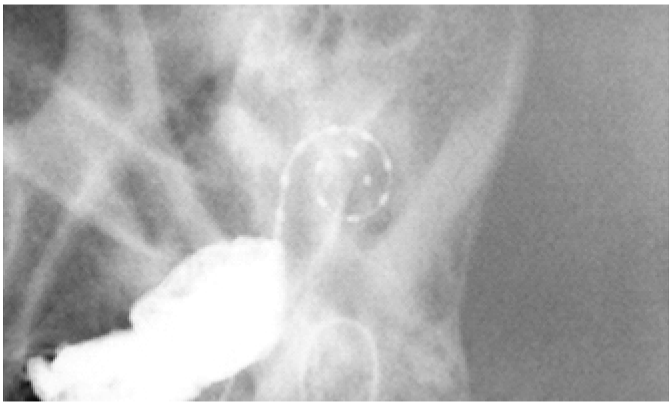


Figure 2 Post-operative X-ray for P3: all electrodes were visualized

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 spiral ganglion 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 organ of Corti), 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 spiral ganglion length. The result was a compressed map, allowing the processor's frequency range to be presented to the area of the cochlea over which spiral ganglion 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 here

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].

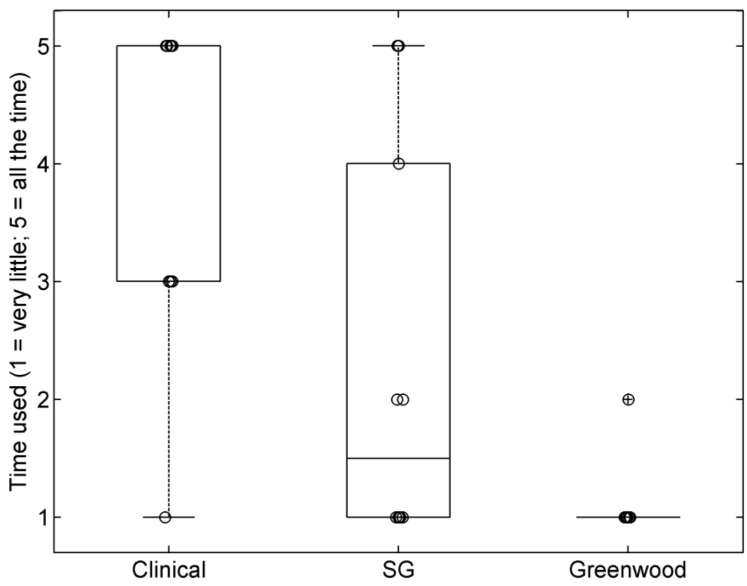


Figure 3 Map use with the clinical, SG and Greenwood maps as reported on the map quality questionnaire at the end of each trial period. Boxes indicate the interquartile range; the solid line within each box indicates the median value. An outlier is displayed as a cross. Individual data points are indicated 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 [$p=0.074$].

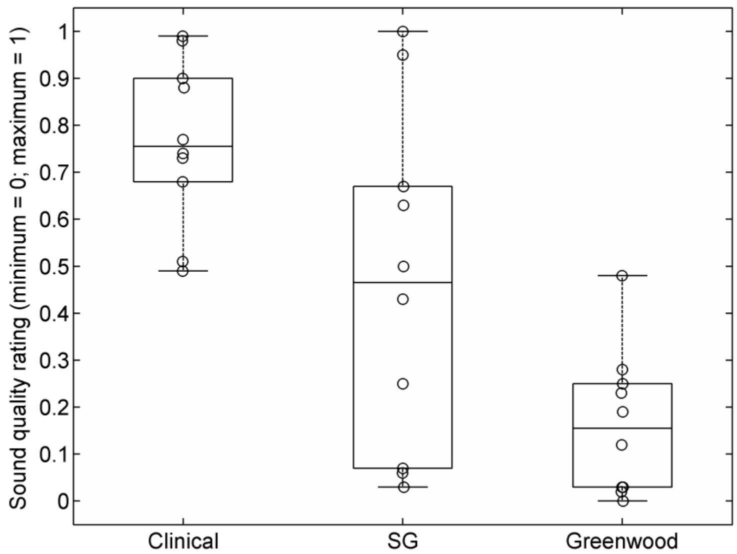


Figure 4 Map quality ratings for the clinical, SG and Greenwood maps as reported on the map quality questionnaire at the end of each trial period. Boxes indicate the interquartile range; the solid line within each box indicates the median value. Individual data points are indicated by small circles.

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].

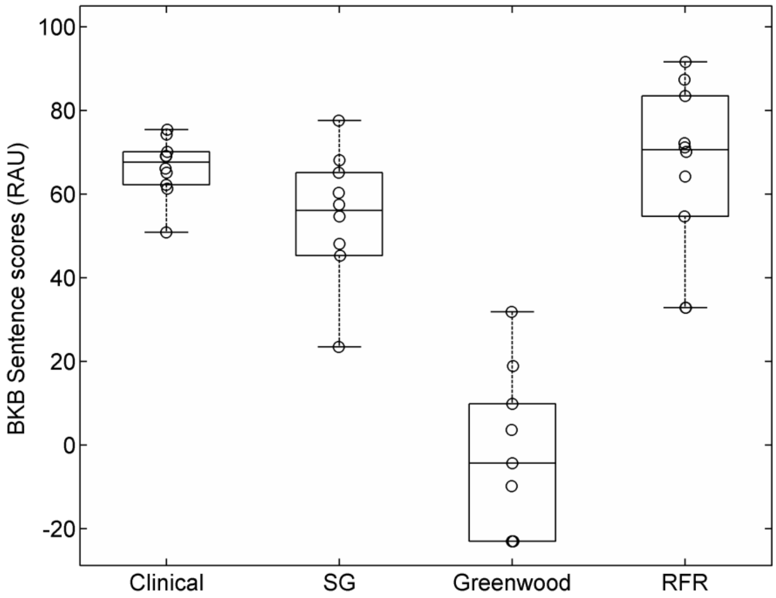


Figure 5 BKB sentence scores for each map at the first test occasion, prior to acclimatization. Boxes indicate the interquartile range; the solid line within each box indicates the median value. Individual data points are indicated by small circles.

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.

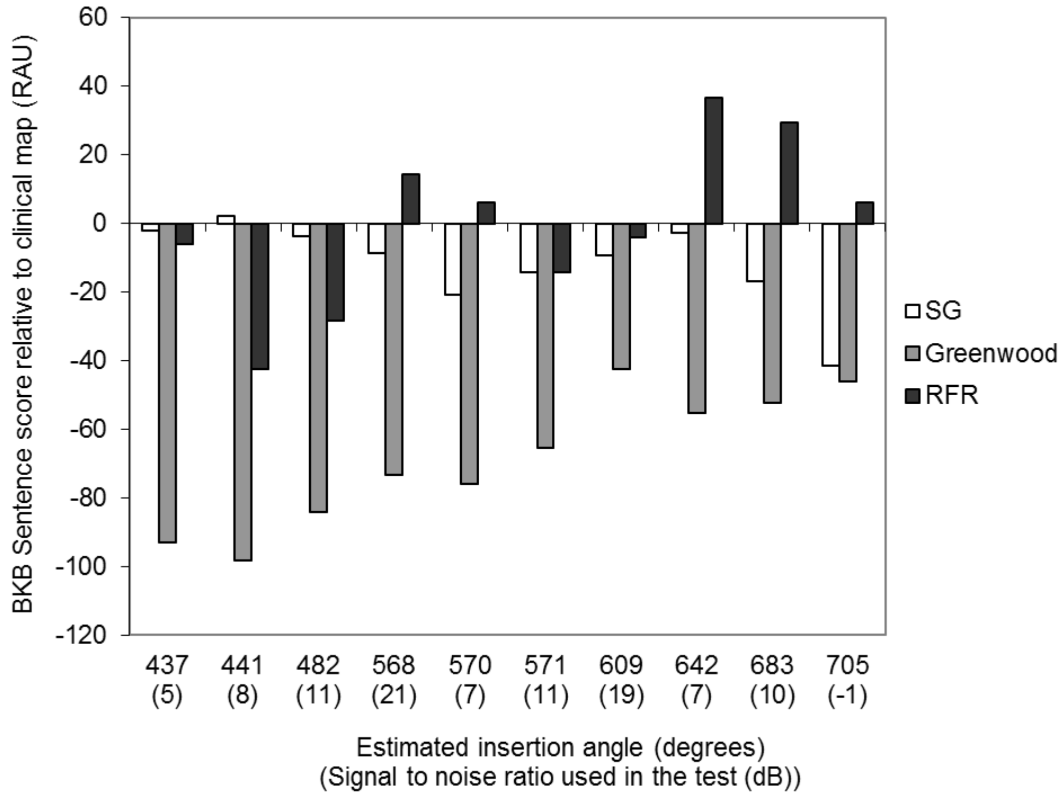


Figure 6 Individual BKB sentence scores when compared to the clinical map. The signal to noise ratio (SNR) used in each test is shown in brackets below the estimated insertion angle.

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].

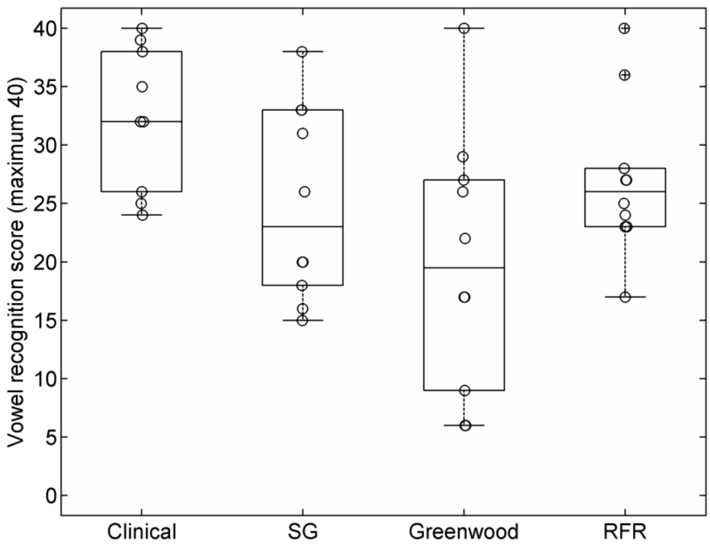


Figure 7 Vowel perception scores for the different frequency allocations. Boxes indicate the interquartile range; the solid line within each box indicates the median value. Outliers are shown by crosses. Individual data points are indicated by small circles.

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].

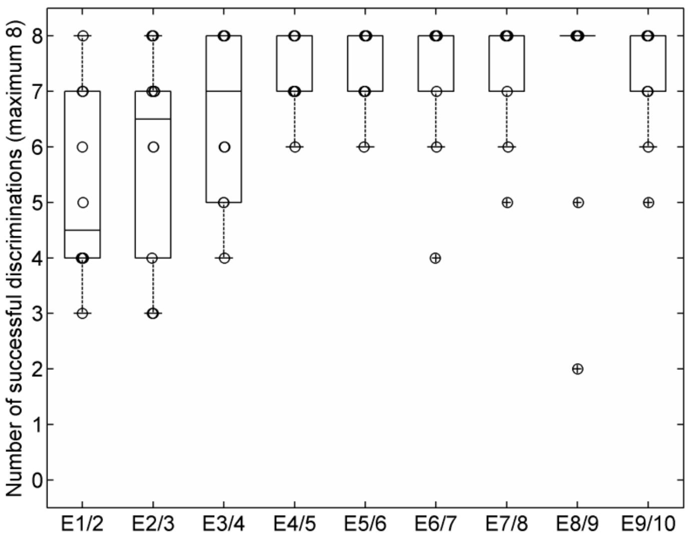


Figure 8 Electrode discrimination scores for individual electrode pairs. Boxes indicate the interquartile range; the solid line within each box indicates the median value. Outliers are shown by crosses. Individual data points are indicated by small circles.

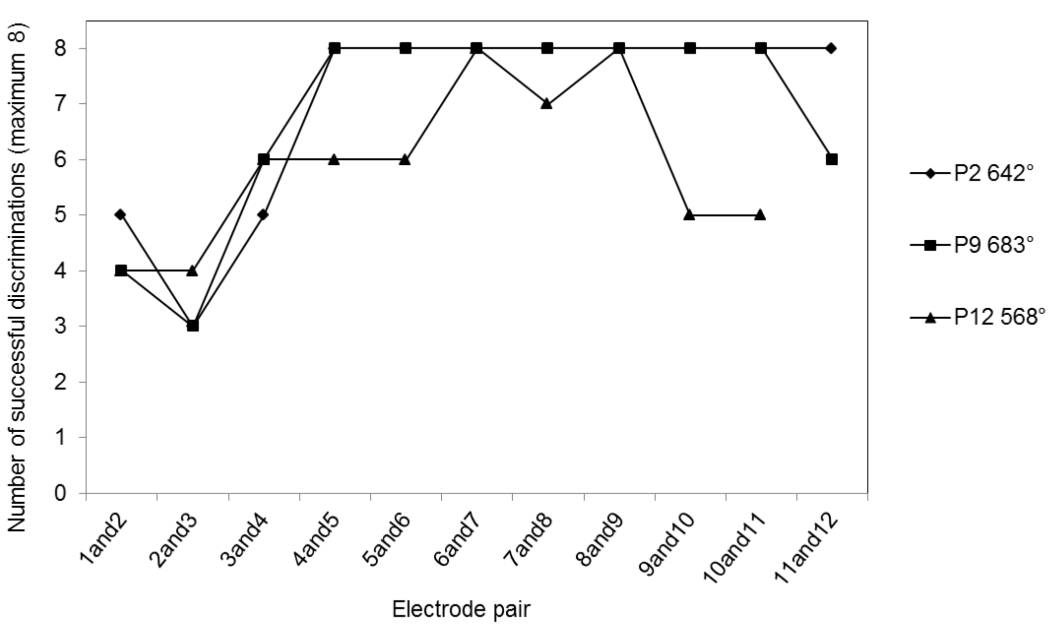
IV DISCUSSION

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).



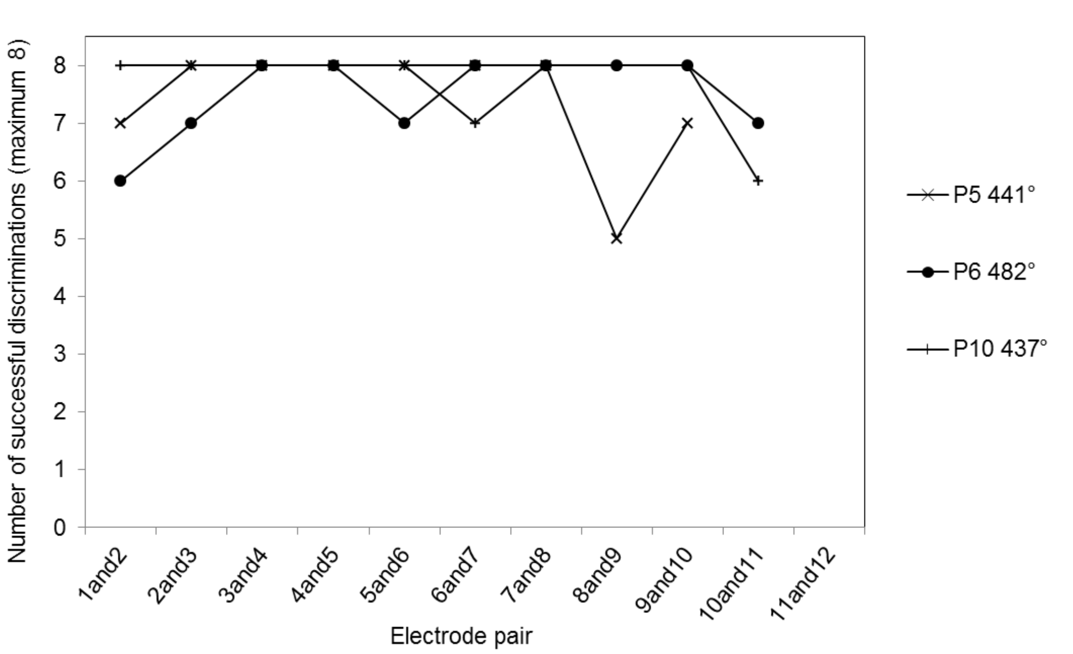


Figure 9 Electrode discrimination scores for (a) those who improved with the RFR map and (b) those who performed worse as shown by a critical difference on the BKB sentence test. The legend shows participant numbers and estimated insertion angles.

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 spiral ganglion 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.

Acknowledgements

The authors would like to thank Dr Steven Bell for his feedback on the study, especially in relation to the statistical analysis.

References

ANSI (**1997**). "Methods for Calculation of the Speech Intelligibility Index," (American National Standards Institute, New York).

Başkent, D., and Shannon, R. V. (**2003**). "Speech recognition under conditions of frequency-place compression and expansion," J. Acoust. Soc. Am. **113**, 2064-2076.

Başkent, D., and Shannon, R. V. (**2004**). "Frequency-place compression and expansion in cochlear implant listeners," J. Acoust. Soc. Am. **116**, 3130-3140.

Başkent, D., and Shannon, R. V. (**2005**). "Interactions between cochlear implant electrode insertion depth and frequency-place mapping," J. Acoust. Soc. Am. **117**, 1405-1416.

Baumann, U., and Nobbe, A. (**2006**). "The cochlear implant electrode-pitch function," Hear. Res. **213**, 34-42.

Baumann, U., Rader, T., Helbig, S., and Bahmer, A. (**2011**). "Pitch Matching Psychometrics in Electric Acoustic Stimulation," Ear Hear. **32**, 656-662.

Bench, J., Kowal, A., and Bamford, J. (**1979**). "The BKB (Bamford-Kowal-Bench) sentence lists for partially-hearing children," Br J Audiol **13**, 108-112.

Boëx, C., Baud, L., Cosendai, G., Sigrist, A., Kos, M. I., and Pelizzone, M. (**2006**). "Acoustic to electric pitch comparisons in cochlear implant subjects with residual hearing," Jaro-Journal of the Association for Research in Otolaryngology **7**, 110-124.

Boyd, P. J. (**2011**). "Potential Benefits From Deeply Inserted Cochlear Implant Electrodes," Ear Hear. **32**, 411-427.

Carlyon, R. P., Macherey, O., Frijns, J. H. M., Axon, P. R., Kalkman, R. K., Boyle, P., Baguley, D. M., Briggs, J., Deeks, J. M., Briaire, J. J., Barreau, X., and Dauman, R. (**2010**). "Pitch Comparisons between Electrical Stimulation of a Cochlear Implant and Acoustic Stimuli Presented to a Normal-hearing Contralateral Ear," Jaro-Journal of the Association for Research in Otolaryngology **11**, 625-640.

Cohen, L. T., Xu, J., Xu, S. A., and Clark, G. M. (**1996**). "Improved and simplified methods for specifying positions of the electrode bands of a cochlear implant array," American Journal of Otology **17**, 859-865.

Di Nardo, W., Cantore, I., Marchese, M. R., Cianfrone, F., Scorpecci, A., Giannantonio, S., and Paludetti, G. (**2008**). "Electric to acoustic pitch matching: a possible way to improve individual cochlear implant fitting," Eur. Arch. Oto-Rhino-Laryn. **265**, 1321-1328.

Di Nardo, W., Scorpecci, A., Giannantonio, S., Cianfrone, F., Parrilla, C., and Paludetti, G. (**2010**). "Cochlear implant patients' speech understanding in background noise: effect of mismatch between electrode assigned frequencies and perceived pitch," Journal of Laryngology and Otology **124**, 828-834.

Dorman, M. F., Loizou, P. C., and Rainey, D. (**1997**). "Simulating the effect of cochlear-implant electrode insertion depth on speech understanding," The Journal of the Acoustical Society of America **102**, 2993-2996.

Dorman, M. F., Spahr, T., Gifford, R., Loiselle, L., McKarns, S., Holden, T., Skinner, M., and Finley, C. (**2007**). "An electric frequency-to-place map for a cochlear implant patient with hearing in the nonimplanted ear," Jaro-Journal of the Association for Research in Otolaryngology **8**, 234-240.

Fayad, J. N., and Linthicum, F. H., Jr. (**2006**). "Multichannel cochlear implants: relation of histopathology to performance," The Laryngoscope **116**, 1310-1320.

Finley, C. C., Holden, T. A., Holden, L. K., Whiting, B. R., Chole, R. A., Neely, G. J., Hullar, T. E., and Skinner, M. W. (**2008**). "Role of Electrode Placement as a Contributor to Variability in Cochlear Implant Outcomes," Otol. Neurotol. **29**, 920-928.

Fourakis, M. S., Hawks, J. W., Holden, L. K., Skinner, M. W., and Holden, T. A. (**2007**). "Effect of frequency boundary assignment on speech recognition with the nucleus 24 ACE speech coding strategy," J. Am. Acad. Audiol. **18**, 700-717.

Fu, Q.-J., and Shannon, R. V. (**2002**). "Frequency mapping in cochlear implants," Ear Hear. **23**, 339-348.

Fu, Q. J., and Shannon, R. V. (**1999a**). "Effects of electrode configuration and frequency allocation on vowel recognition with the nucleus-22 cochlear implant," Ear Hear. **20**, 332-344.

Fu, Q. J., and Shannon, R. V. (**1999b**). "Effects of electrode location and spacing on phoneme recognition with the nucleus-22 cochlear implant," Ear Hear. **20**, 321-331.

Fu, Q. J., and Shannon, R. V. (**1999c**). "Recognition of spectrally degraded and frequency-shifted vowels in acoustic and electric hearing," J. Acoust. Soc. Am. **105**, 1889-1900.

Gani, M., Valentini, G., Sigrist, A., Kos, M. I., and Boëx, C. (**2007**). "Implications of deep electrode insertion on cochlear implant fitting," Jaro-Journal of the Association for Research in Otolaryngology **8**, 69-83.

Gfeller, K., Turner, C., Oleson, J., Zhang, X. Y., Gantz, B., Froman, R., and Olszewski, C. (**2007**). "Accuracy of cochlear implant recipients on pitch perception, melody recognition, and speech reception in noise," Ear Hear. **28**, 412-423.

Goupell, M. J., Laback, B., Majdak, P., and Baumgartner, W. D. (**2008**). "Effects of upper-frequency boundary and spectral warping on speech intelligibility in electrical stimulation," J. Acoust. Soc. Am. **123**, 2295-2309.

Greenwood, D. D. (**1990**). "A Cochlear Frequency-Position Function for Several Species - 29 Years Later," J. Acoust. Soc. Am. **87**, 2592-2605.

Kawano, A., Seldon, H. L., and Clark, G. M. (**1996**). "Computer-aided three-dimensional reconstruction in human cochlear maps: Measurement of the lengths of organ of corti, outer wall, inner wall, and Rosenthal's canal," Annals of Otology Rhinology and Laryngology **105**, 701-709.

Li, T. H., Galvin, J. J., and Fu, Q. J. (**2009**). "Interactions Between Unsupervised Learning and the Degree of Spectral Mismatch on Short-Term Perceptual Adaptation to Spectrally Shifted Speech," Ear Hear. **30**, 238-249.

Martin, M. (ed). (**1997**). *Speech Audiometry Second Edition* (Whurr Publishers Ltd, London), pp. 172-175.

McKay, C. M., and Henshall, K. R. (**2002**). "Frequency-to-electrode allocation and speech perception with cochlear implants," J. Acoust. Soc. Am. **111**, 1036-1044.

Nelson, D. A., Vantasell, D. J., Schroder, A. C., Soli, S., and Levine, S. (**1995**). "Electrode Ranking of place pitch and speech recognition in electrical hearing," J. Acoust. Soc. Am. **98**, 1987-1999.

Radeloff, A., Mack, M., Baghi, M., Gstoettner, W. K., and Adunka, O. F. (**2008**). "Variance of angular insertion depths in free-fitting and perimodiolar cochlear implant electrodes," Otol. Neurotol. **29**, 131-136.

Riss, D., Hamzavi, J. S., Selberherr, A., Kaider, A., Blineder, M., Starlinger, V., Gstoettner, W., and Arnoldner, C. (**2011**). "Envelope Versus Fine Structure Speech Coding Strategy: A Crossover Study," Otol. Neurotol. **32**, 1094-1101.

Rosen, S., Faulkner, A., and Wilkinson, L. (**1999**). "Adaptation by normal listeners to upward spectral shifts of speech: Implications for cochlear implants," J. Acoust. Soc. Am. **106**, 3629-3636.

Sagi, E., Fu, Q. J., Galvin, J. J., and Svirsky, M. A. (**2010**). "A Model of Incomplete Adaptation to a Severely Shifted Frequency-to-Electrode Mapping by Cochlear Implant Users," Jaro-Journal of the Association for Research in Otolaryngology **11**, 69-78.

Shannon, R. V., Zeng, F. G., and Wygonski, J. (**1998**). "Speech recognition with altered spectral distribution of envelope cues," The Journal of the Acoustical Society of America **104**, 2467-2476.

Simpson, A., McDermott, H. J., Dowell, R. C., Sucher, C., and Briggs, R. J. S. (**2009**). "Comparison of two frequency-to-electrode maps for acoustic-electric stimulation," Int. J. Audiol. **48**, 63-73.

Skinner, M. W., Holden, T. A., Whiting, B. R., Voie, A. H., Brunsden, B., Neely, J. G., Saxon, E. A., Hullar, T. E., and Finley, C. C. (**2007**). "In vivo estimates of the position of advanced bionics electrode arrays in the human cochlea," Annals of Otology Rhinology and Laryngology **116**, 2-24.

Sridhar, D., Stakhovskaya, O., and Leake, P. A. (**2006**). "A frequency-position function for the human cochlear spiral ganglion," Audiol Neurootol **11 Suppl 1**, 16-20.

Stakhovskaya, O., Sridhar, D., Bonham, B. H., and Leake, P. A. (**2007**). "Frequency map for the human cochlear spiral ganglion: Implications for cochlear implants," Jaro-Journal of the Association for Research in Otolaryngology **8**, 220-233.

Studebaker, G. A. (**1985**). "A rationalized arcsine transform," Journal of Speech and Hearing Research **28**, 455-462.

Svirsky, M. A., Silveira, A., Neuburger, H., Teoh, S. W., and Suarez, H. (**2004**). "Long-term auditory adaptation to a modified peripheral frequency map," Acta Oto-Laryngol. **124**, 381-386.

Ulehlova, L., Voldrich, L., and Janisch, R. (**1987**). "Correlative study of sensory cell-density and cochlear length in humans," Hear. Res. **28**, 149-151.

van Besouw, R. M., and Grasmeder, M. L. (**2011**). "From TEMPO+ to OPUS 2: what can music tests tell us about processor upgrades?," Cochlear Implants International **12 Suppl 2**, S40-43.

Vermeire, K., Nobbe, A., Schleich, P., Nopp, P., Voormolen, M. H., and Van de Heyning, P. H. (**2008**). "Neural tonotopy in cochlear implants: An evaluation in unilateral cochlear implant patients with unilateral deafness and tinnitus," Hear. Res. **245**, 98-106.

Whitmal, N. A., and DeRoy, K. (**2012**). "Use of an adaptive-bandwidth protocol to measure importance functions for simulated cochlear implant frequency channels," J. Acoust. Soc. Am. **131**, 1359-1370.

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

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°

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

Figure Captions

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

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

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.

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.

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.

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.

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.

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.

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 different on the BKB sentence test. The legend shows participant numbers and estimated insertion angles.