Abstract (not more than 250 words)

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 (R2=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 (R2=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.

Keywords: Cochlear Implant; Music; Pitch; Frequency; Sound Quality; Mapping; Tuning

**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. 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, which is described by the Greenwood function (Greenwood, 1990). 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 perceived pitch is similar to acoustic pitch (Vermeire et al., 2008, Carlyon et al., 2010), whilst other studies have reported pitch percepts below the Greenwood function (Dorman et al., 2007, Boex et al., 2006, Simpson et al., 2009, Baumann and Nobbe, 2006).

Changes in pitch between adjacent electrodes were also found to be less than expected: 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 Boex 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.

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.

Table 1 here

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.

Figure 1 here

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 and 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 here

**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.

Figure 3 here

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 here

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 here

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 here

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**

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 here

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 here

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 here

**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.

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 here

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, Boex 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.

References

BAUMANN, U. & NOBBE, A. 2006. The cochlear implant electrode-pitch function. *Hearing Research,* 213**,** 34-42.

BAUMANN, U., RADER, T., HELBIG, S. & BAHMER, A. 2011. Pitch Matching Psychometrics in Electric Acoustic Stimulation. *Ear and Hearing,* 32**,** 656-662.

BOEX, C., BAUD, L., COSENDAI, G., SIGRIST, A., KOS, M. I. & 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 and Hearing,* 32**,** 411-427.

BROCKMEIER, S. J., FITZGERALD, D., SEARLE, O., FITZGERALD, H., GRASMEDER, M., HILBIG, S., VERMIERE, K., PETERREINS, M., HEYDNER, S. & ARNOLD, W. 2011. The MuSIC perception test: a novel battery for testing music perception of cochlear implant users. *Cochlear implants international,* 12**,** 10-20.

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. & 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., RICHARDSON, L. M., SAUNDERS, E. & COWAN, R. S. C. 2003. Spatial spread of neural excitation in cochlear implant recipients: comparison of improved ECAP method and psychophysical forward masking. *Hearing Research,* 179**,** 72-87.

COOPER, W. B., TOBEY, E. & LOIZOU, P. C. 2008. Music perception by cochlear implant and normal hearing listeners as measured by the Montreal Battery for Evaluation of Amusia. *Ear and Hearing,* 29**,** 618-626.

DORMAN, M. F., SPAHR, T., GIFFORD, R., LOISELLE, L., MCKARNS, S., HOLDEN, T., SKINNER, M. & 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.

DRENNAN, W. R., OLESON, J. J., GFELLER, K., CROSSON, J., DRISCOLL, V. D., WON, J. H., ANDERSON, E. S. & RUBINSTEIN, J. T. 2015. Clinical evaluation of music perception, appraisal and experience in cochlear implant users. *International Journal of Audiology,* 54**,** 114-123.

FRANKE-TRIEGER, A., JOLLY, C., DARBINJAN, A., ZAHNERT, T. & MUERBE, D. 2014. Insertion Depth Angles of Cochlear Implant Arrays With Varying Length: A Temporal Bone Study. *Otology & Neurotology,* 35**,** 58-63.

GALVIN, J. J., III & FU, Q.-J. 2011. Effect of bandpass filtering on melodic contour identification by cochlear implant users. *Journal of the Acoustical Society of America,* 129**,** EL39-EL44.

GALVIN, J. J., III, FU, Q.-J. & NOGAKI, G. 2007. Melodic contour identification by cochlear implant listeners. *Ear and Hearing,* 28**,** 302-319.

GALVIN, J. J., III, FU, Q.-J. & OBA, S. I. 2009. Effect of a competing instrument on melodic contour identification by cochlear implant users. *Journal of the Acoustical Society of America,* 125**,** EL98-EL103.

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.

KANG, R., NIMMONS, G. L., DRENNAN, W., LONGNION, J., RUFFIN, C., NIE, K., WON, J. H., WORMAN, T., YUEH, B. & RUBINSTEIN, J. 2009. Development and Validation of the University of Washington Clinical Assessment of Music Perception Test. *Ear and Hearing,* 30**,** 411-418.

LANDSBERGER, D. & GALVIN, J. J., III 2011. Discrimination between sequential and simultaneous virtual channels with electrical hearing. *Journal of the Acoustical Society of America,* 130**,** 1559-1566.

LEVITIN, D. J. 1994. ABSOLUTE MEMORY FOR MUSICAL PITCH - EVIDENCE FROM THE PRODUCTION OF LEARNED MELODIES. *Perception & Psychophysics,* 56**,** 414-423.

LIMB, C. J. & ROY, A. T. 2014. Technological, biological, and acoustical constraints to music perception in cochlear implant users. *Hearing Research,* 308**,** 13-26.

LOOI, V., MCDERMOTT, H., MCKAY, C. & HICKSON, L. 2008. Music perception of cochlear implant users compared with that of hearing aid users. *Ear and Hearing,* 29**,** 421-434.

MCDERMOTT, H. J. 2004. Music perception with cochlear implants: a review. *Trends Amplif,* 8**,** 49-82.

MOORE, B. C. J. & TAN, C. T. 2003. Perceived naturalness of spectrally distorted speech and music. *Journal of the Acoustical Society of America,* 114**,** 408-419.

PHILIPS, B., VINCK, B., DE VEL, E., MAES, L., D'HAENENS, W., KEPPLER, H. & DHOOGE, I. 2012. Characteristics and determinants of music appreciation in adult CI users. *European Archives of Oto-Rhino-Laryngology,* 269**,** 813-821.

PLANT, K. L., MCDERMOTT, H. J., VAN HOESEL, R. J. M., DAWSON, P. W. & COWAN, R. S. 2014. Factors influencing electrical place pitch perception in bimodal listeners. *Journal of the Acoustical Society of America,* 136**,** 1199-1211.

RADELOFF, A., MACK, M., BAGHI, M., GSTOETTNER, W. K. & ADUNKA, O. F. 2008. Variance of angular insertion depths in free-fitting and perimodiolar cochlear implant electrodes. *Otology & Neurotology,* 29**,** 131-136.

REISS, L. A. J., ITO, R. A., EGGLESTON, J. L., LIAO, S., BECKER, J. J., LAKIN, C. E., WARREN, F. M. & MCMENOMEY, S. O. 2015. Pitch adaptation patterns in bimodal cochlear implant users: over time and after experience. *Ear and hearing,* 36**,** e23-34.

REISS, L. A. J., TURNER, C. W., ERENBERG, S. R. & GANTZ, B. J. 2007. Changes in pitch with a cochlear implant over time. *Jaro-Journal of the Association for Research in Otolaryngology,* 8**,** 241-257.

ROY, A. T., JIRADEJVONG, P., CARVER, C. & LIMB, C. J. 2012. Assessment of Sound Quality Perception in Cochlear Implant Users During Music Listening. *Otology & Neurotology,* 33**,** 319-327.

SIMONYAN, A. 2012. Pitch discrimination of cochlear implant users depending on the stimulations place and the stimulations rate. *Elektrotechnik und Informationstechnik,* 129**,** 102-6.

SIMPSON, A., MCDERMOTT, H. J., DOWELL, R. C., SUCHER, C. & BRIGGS, R. J. S. 2009. Comparison of two frequency-to-electrode maps for acoustic-electric stimulation. *International Journal of Audiology,* 48**,** 63-73.

STAKHOVSKAYA, O., SRIDHAR, D., BONHAM, B. H. & 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.

VAN BESOUW, R. M. & GRASMEDER, M. L. 2011. From TEMPO+ to OPUS 2: what can music tests tell us about processor upgrades? *Cochlear implants international,* 12 Suppl 2**,** S40-3.

VAN BESOUW, R. M., NICHOLLS, D. R., OLIVER, B. R., HODKINSON, S. M. & GRASMEDER, M. L. 2014. Aural Rehabilitation through Music Workshops for Cochlear Implant Users. *Journal of the American Academy of Audiology,* 25**,** 311-323.

VAN DER MAREL, K. S., BRIAIRE, J. J., WOLTERBEEK, R., SNEL-BONGERS, J., VERBIST, B. M. & FRIJNS, J. H. M. 2014. Diversity in Cochlear Morphology and Its Influence on Cochlear Implant Electrode Position. *Ear and Hearing,* 35**,** E9-E20.

VERMEIRE, K., NOBBE, A., SCHLEICH, P., NOPP, P., VOORMOLEN, M. H. & VAN DE HEYNING, P. H. 2008. Neural tonotopy in cochlear implants: An evaluation in unilateral cochlear implant patients with unilateral deafness and tinnitus. *Hearing Research,* 245**,** 98-106.

ZENG, F.-G., TANG, Q. & LU, T. 2014. Abnormal Pitch Perception Produced by Cochlear Implant Stimulation. *Plos One,* 9.

ZENG, F. G. 2002. Temporal pitch in electric hearing. *Hearing Research,* 174**,** 101-106.

ZHU, M., CHEN, B., GALVIN, J. J., III & FU, Q.-J. 2011. Influence of pitch, timbre and timing cues on melodic contour identification with a competing masker (L). *Journal of the Acoustical Society of America,* 130**,** 3562-3565.

Tables

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| --- | --- | --- | --- | --- | --- |
| 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 |

Table 1 Study participants’ details

Figure captions

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

Figure 2 Graphical user interface for the mixer app in IMAP

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.

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

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.

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

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.

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.

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

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.







