## Abstract

Objective: To investigate the possibility that speech perception could be improved for some cochlear implant (CI) users by adjustment of the frequency allocation to the electrodes, following assessment of pitch perception along the electrode array.

Design: In this study, pitch perception was assessed for individual CI electrode pairs using the Pitch Contour Test (PCT), giving information on pitch discrimination and pitch ranking. Sentence perception in noise was also assessed with ten different frequency allocations, including the default.

Study sample: Thirteen adult CI users participated in the study.

Results: Pitch perception was poorer for both discrimination and ranking scores at either end of the electrode array. A significant effect of frequency allocation was found for sentence scores [$F(4.24,38.2)=7.14$, $p<0.001$] and a significant interaction between sentence score and PCT ranking score for basal electrodes was found [$F(4.24,38.2)=2.95$, $p=0.03$]. Participants with poorer pitch perception at the basal end had poorer scores for some allocations with greater basal shift.

Conclusions: The results suggest that speech perception could be improved for CI users by assessment of pitch perception using the PCT and subsequent adjustment of pitch-related stimulation parameters.

Cochlear implantation is a well-established treatment for deafness which restores access to sound and provides high levels of benefit to speech perception and other listening skills. However, the extent of benefit depends in part on optimal tuning of the device for the individual, which is typically focused on adjustment of electrical threshold and comfort levels and not individualised adjustment of CI parameters relating to coding of frequency information (frequency range, choice of activated channels, or frequency allocation to electrodes). Speech perception can be improved if electrodes associated with poor pitch perception are removed from an individual's map (Zwolan et al., 1997; Gani et al., 2007; van Besouw & Grasmeder, 2011; Saleh et al., 2013). Pitch perception can be markedly abnormal for some electrodes for individual CI users, so this approach ensures that stimulation is targeted towards areas of better pitch perception. However, it may limit frequency resolution, as the implant's frequency range may need to be accommodated within a more restricted area of the cochlea. An alternative approach is to adjust the frequency allocation, so that frequencies important for speech perception are moved away from areas of poor perception to areas of better pitch perception. In practice, there is a trade-off between frequency range and frequency resolution, but modest truncation of the range may be worthwhile to maintain better frequency resolution (through the narrower bandwidth that can be achieved per frequency channel).

We have previously shown that, for users of the MED-EL device with poor pitch perception at the apical end of the array, acute improvements in speech recognition could be achieved with these changes (Grasmeder et al., 2014), despite the fact that participants had no time to acclimatise to the pitch changes associated with altered frequency allocation. By contrast, for participants with good pitch perception at the apical end of the electrode array, the adjusted allocation led either to no improvement or to deterioration in speech recognition. These findings are encouraging but beg the question of how pitch perception can best be assessed clinically in order to inform these mapping choices. A range of techniques have been proposed in the literature for assessment of pitch perception, including electrode ranking or discrimination (Nelson et al., 1995; Zwolan, Collins et al., 1997; Baumann & Nobbe, 2004; Gani, Valentini et al., 2007; Saleh, Saeed et al., 2013; Vickers et al., 2016), pitch scaling (Boyd, 2011), multi-dimensional scaling (Henshall & McKay, 2001; McKay & Henshall, 2002), pitch matching (Di Nardo et al., 2010)(albeit only viable when there is contralateral residual hearing) and tests that use musical stimuli (see for example (Galvin et al., 2007)).

We propose a novel method of pitch perception testing, the Pitch Contour Test (PCT), to guide CI tuning. The PCT is a three-interval, four-alternative forced choice test (3I4AFC test), which requires the listener to determine if the first or last note of three consecutive notes is the odd one out, and if the odd note is higher or lower in pitch than the other two. In order to assess pitch perception, loudness and timing cues are minimised during the test. The PCT test was developed initially as a test of music perception and is described in detail in a companion paper (Wheatley et al., in preparation). The test was modified to allow electrode centre frequencies to be tested, for tuning purposes. It meets some key requirements which are not fully met in current approaches. First, the test allows specific pitch comparisons between different electrode channels. Second, both pitch discrimination and pitch ranking (or contour) are measured concurrently. This widens the potential application of the test in that subtler disturbances of pitch perception can be detected with pitch contour perception but not pitch discrimination, while pitch discrimination is an easier task that may be achievable by a wider range of individuals than pitch ranking. Third, stimulus presentation is achieved via standard programming software rather than requiring specialist equipment to support direct stimulation. Stimuli are presented acoustically via headphones or other means, such as the Otocube box (Matos Magalhães et al., 2014). The test uses the method of constant stimuli and includes a relatively large number of trials in each run for a clinical test (n=32). This yields separate discrimination and ranking scores for any electrode pair tested.

We report a two-part experiment in a cohort of adult users of the MED-EL standard and Flex28 electrode arrays. The MED-EL device was chosen as (i) its longer electrode length meaning a wider region of the cochlea can be assessed for pitch perception, (ii) it uses a smaller number of electrodes (12) compared to other devices and (iii) frequency allocation via the programming software is highly flexible. We first used the PCT in order to characterise individual variations in place-pitch perception along the electrode array, and to determine the clinical viability of the test, including time taken, subject acceptance and avoidance of floor and ceiling effects. The same CI users were tested with different frequency allocation to electrodes with differing amounts of shift towards basal electrodes compared to default setting. The basal shift was achieved by using a logarithmic-shaped frequency map for the study maps with a limited amount of truncation of the frequency range at one or both ends of the frequency range. The default frequency map is based on a polynomial function and uses a wide frequency range (100 – 8500 Hz). It was hypothesised that, if individual CI users had poor pitch perception at the apical end of the array (as shown by the PCT), some degree of basal shift and a reduction in the allocation of frequencies to the apical electrodes would benefit speech in noise perception and other pitch-based tasks.

# Methods

*Participants and methods*

Thirteen unilaterally-implanted, post-lingually deafened adult CI users were recruited for the experiment. All participants had been implanted for at least one year and had MED-EL CIs with either a standard (N=7) or Flex28 (N=6) electrode array. All participants had a full insertion of the electrode array according to the surgeon's notes. Participants performed the test for all of their active electrodes (E) in a pseudo-randomised order. Testing was separated into two sessions, either on the same day (with a substantial break) or on different days. All participants scored at least 80% correct on the Bamford Kowal Bench (BKB) sentence test (Bench et al., 1979) in quiet at their most recent annual review. All participants used the default frequency allocation. 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. Part 2 of the experiment (which involved adjustment of frequency allocation settings) was conducted during the same test sessions as part 1. Take-home experience was not incorporated into the design of the experiment, as the intention was to test a large number of frequency allocation settings. The frequency shift was limited to less than one octave, in order to limit the need for acclimatisation.

*The Pitch Contour Test*

The 3I4AFC test uses the method of constant stimuli. There are 32 trials in each test. Each trial consists of a presentation of three pure tones, two of which have the same frequency. Participants are asked to identify the order in which the sounds are presented (in terms of pitch) out of four possibilities: low/high/high, high/low/low, low/low/high or high/high/low. The four alternatives are represented on the graphical users interface by black dots, as shown in figure 1. The participant indicates their choice by selecting the appropriate button using a computer mouse or touch screen. A correct response is given for discrimination if the odd note out is identified correctly and for contour if both the odd note out and the direction of pitch change is identified correctly.

Figure 1 here

In order to assess place-pitch perception, minimise temporal pitch cues and to use the test for electrode-specific investigations with the MED-EL Opus 2 speech processor, pure tones at frequencies of 750 and 1150 Hz were created for use as the test stimuli. These frequencies are above the frequency range over which pitch cues are likely to be perceived from the frequency of modulation within the temporal envelope (Shannon, 1983), which may occur when a high-rate sound coding strategy is used with a low frequency tone. A new map was made for each electrode pair and activated for the duration of the test only. The centre frequencies of the electrodes being tested were adjusted to the same frequencies as the test stimuli, to ensure that only the desired electrode was stimulated. The strategy used was High Definition Continuous Interleaved Sampling (HDCIS), in order to avoid additional temporal cues associated with the fine structure processing (FSP) strategies. The rate of stimulation was the same as the rate in the participant's default map if the participant used the FSP strategy in their everyday map, or was adjusted to 1500 Hz if the participant used the FS4 or FS4-p strategy in their everyday map. The presentation level was set to 60 dB (A) with ± 2 dB of loudness roving, and the processor's microphone frequency response and the processor's pre-emphasis filter were taken into account when the stimuli were produced, in order to equalise loudness as far as possible. Loudness balancing was performed at 90% of Maximum Comfort Level (MCL), as the test tones produce stimulation at approximately this level. All other electrodes were deactivated for the duration of the test. As an additional safeguard against spurious level cues, the same processor was used for all tests, and the test was presented in Otocube, a soundproof box containing a loudspeaker, which gives very repeatable levels (within 0.5 dB) for frequencies within the range of 300 - 1500 Hz.

Participants first underwent a practice run with 12 trials, in which feedback was given. Participants used their everyday map for the practice run. Pure tones with frequencies of 375 and 1500 Hz were compared for the first 8 trials in the practice run, followed by 750 and 1500 Hz for the remaining 4 trials. Typically, this would produce stimulation primarily on electrodes three and seven in the first eight trials and electrodes five and seven in the last four trials. Participants repeated each trial until they obtained the correct answer. For each trial, there is a 50% chance of getting the discrimination task correct as two of the four alternatives have either the first note or the third note as the odd note out. There is a 25% chance of getting the pitch contour (pitch ranking task) correct, as only one of the alternatives has the correct note (first or third) moving in the correct direction from the previous note (either up or down). However, during the main test, a score of 22/32 was required to be considered significantly above chance for both tasks. This is based on calculating the probability of a correct score being obtained by chance of less than 5%, from the binomial theory with a chance score of 50%. This was thought to be appropriate for the contour score as well as the discrimination score, as if a participant has the ability to discriminate the pitch of the notes (eliminating two of the contours), there will be a 50% chance of correctly ranking the remaining two contours.

*Adjustment of CI frequency allocations*

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

The map L0U0 had the same frequency allocation as the default map for basal electrodes, but had a different frequency allocation function shape for the apical electrodes and some associated apical shift for those electrodes, as shown in Figure 2(a). It was anticipated that this map would have the lowest pitch percept. The amount of basal shift was measured relative to this map. The numbers 1 and 2 for the lower and upper frequency boundaries represent shifts of one third (400 cents) and two thirds (800 cents) of an octave respectively, so the map L2U2 has a basal shift of two thirds of an octave across the whole electrode array, when compared to map L0U0. Map L0U2 had no frequency shift at the apical end, but a frequency shift of two thirds of an octave at the basal end. Maps L1U0 and L1U1 are shown in Figure 2(b). The centre frequencies for all maps are shown in Table 2.

Figure 2 here

Table 2 here

For participants with the FSP strategy, some of the alternative maps had a different number of fine structure channels. When compared with the default map, there was an increase in the number of fine structure channels by one for P5 and for P12 for the four most basal maps. For P9, there was an increase of one fine structure channel for the L2 maps but a decrease from one to zero fine structure channels for maps L0U0 and L0U1; an increase in the number of fine structure channels might increase the temporal cues available to these participants for these maps. No electrodes were deactivated in order to fit any of the experimental maps, so for each participant the number of electrodes activated in each map was the same as for their normal clinical (default) map. There were no changes to the rate of stimulation or any other parameter between maps.

*Test materials*

The BKB sentence test was used to assess speech perception. New extended lists of sentences were used for this experiment, which were presented via the AstonSoundLite program (use of the standard lists would have required all the available sentences to be presented, which could impact on normal clinical assessments). The extended sentences use the same vocabulary as the original sentences, have the same number of keywords per sentence and are spoken by the same speaker. The sentences were organised into lists. Sentences were presented in speech-shaped noise at 65 dB(A) and the SNR for which the participant scored between 60 to 70% correct with their everyday clinical map was found. For the measurement of performance with each frequency allocation, 10 lists of 32 sentences each containing 100 keywords were used and again there was no repetition of a keyword within a list. The order of testing of the maps was pseudo-randomised; five maps were tested in the first session and the remaining five in the second session for each participant. The sentences were presented via a sound-treated box containing a loudspeaker, Otocube. A test processor (Opus 2), connected to a long coil cable, was used throughout.

## Results

*Individual results and test viability*

All thirteen participants were able to complete the test, although three required help from the operator. In two cases, participants were unfamiliar with using a computer and required help with using the mouse. One participant found the graphical user interface confusing and gave verbal feedback to the operator. This participant was able to say, for example, ‘High, low, low’ or ‘Low, high, high’ but was unable to relate these statements to the visual representations of them on the screen. A realistic total testing time of 40 minutes was achieved for testing of five electrode pairs.

This included time to prepare the maps used in the test, to loudness balance the comfort levels of the maps, to train the participant in the procedure, to undertake a practise run and then to run the test itself, which ranged from 1 to 5 minutes per electrode pair tested, although this was slightly longer for the two participants who required assistance. Performance was scored separately for pitch contour and pitch discrimination. A summary of results for all participants and all electrode pairs is shown in Figure 3.

Figure 3 here

It was found that four participants were able to score above chance (score ≥ 22/32) for all electrode pairs for both contour and discrimination (P1, P4, P9 and P10). Four participants had some difficulty at both ends of the array (P5, P6, P7 and P13), whilst two participants had difficulties at the apical end only (P11 and P12) and two participants had difficulties at the basal end of the array only (P2 and P3). One participant had difficulty with the contour for one electrode pair in the middle of the array (P8). PCT scores for all participants are shown in figure 4.

Figure 4 here

*Electrode pair performance*

Discrimination scores for all electrodes for the group are shown in figure 5. Analysis was performed for the eleven participants who had all electrodes active in their map. Scores were not normally distributed for any of the electrode pairs for discrimination or contour scores. Friedman's test was used to analyse discrimination scores. A significant effect of electrode pair was found [$\chi^2(10)=34.2$, $p<0.001$]. Individual electrode pairs were compared using the Wilcoxon signed ranks test. All electrode pairs were compared with electrode pair E6E7, as these electrodes are in the middle of the array. It was found that electrode pairs E1E2 and also E11E12 gave poorer results on the discrimination part of the test than electrodes E6E7 [$Z=-2.53$, $p=0.011$, $r=0.57$ for electrodes 1 and 2; $Z=-2.53$, $p=0.012$, $r=0.57$ for electrodes 11 and 12 (both large effects)]. Bonferroni corrections were not applied, as this would have contradicted the result of Friedman's test.

Figure 5 here

Friedman's test was used to analyse the contour scores, which are shown in figure 6. A significant effect of electrode pair was found [$\chi^2(10)=46.5$, $p<0.001$]. Individual electrode pairs were compared using the Wilcoxon signed ranks test (2-tailed). It was found that electrode pairs E1E2, E2E3, E8E9, E10E11 and E11E12 all offered poorer performance than electrode pair E6E7. However, no Bonferroni corrections were applied, to be consistent with the discrimination test results [$Z=-2.668$, *p*=0.008, *r*=-0.52 for E1E2; *Z* =-1.97, *p*=0.049, *r*=-0.39 for E2E3; *Z*=-2.23, *p*=0.026, *r*=-0.44 for E8E9; *Z*=-2.671, *p*=0.008, *r*=-0.52 for E10E11 and *Z*=-2.807, *p*=0.005, *r*=-0.55 for E11E12]. There were large effects for electrode pairs E1E2, E10E11 and E11E12; there were medium effects for E2E3 and E8E9.

Figure 6 here

*Effect of frequency allocation*

BKB sentence scores for the group are shown in figure 7. The influence of PCT Contour score for apical electrodes and basal electrodes was investigated within the analysis of BKB scores. A two-way repeated-measures analysis of variance (ANOVA) was performed with between-subjects measures of PCT score for apical electrodes and also PCT score for basal electrodes. The PCT score for apical electrodes was either chance or above chance, based on the PCT score for electrode pairs E1E2 and E2E3. Similarly, the PCT score for basal electrodes was either chance or above chance, based on the PCT score for electrode pairs E10E11 and E11E12. Mauchly's test of sphericity gave a significant result for this data: [$\chi^2(44)=93.1$, $p<0.001$]. The Greenhouse-Geisser correction was applied in view of this. The ANOVA showed a significant main effect of map on BKB sentence test score [$F(4.24,38.2)=7.14$, $p<0.001$]. There was no independent effect of PCT score for basal electrodes [$F(1,9)=0.865$, $p>0.05$] or apical electrodes [$F(1,9)=0.289$, $p>0.05$]. However, there was a significant interaction between BKB score and PCT contour score for basal electrodes [$F(4.24,38.2)=2.95$, $p=0.03$], but no significant interaction between BKB score and PCT score for apical electrodes [$F(4.24,38.2)=1.31$, $p>0.05$].

Figure 7 here

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

Within-subjects contrasts investigating the interaction between PCT score for basal electrodes and BKB sentence score indicated an interaction between BKB sentence score and basal PCT score for the L1U1 map, when compared to the L0U0 map [*p*=0.008, *r*=0.75, a large effect] and to a lesser extent for the L0U1 map [*p*=0.033, *r*=0.64], L1U2 map [*p*=0.018, *r*=0.69] and L2U2 maps [*p*=0.042, *r*=0.62], all large effects. However, these contrasts were made without Bonferroni corrections, which would have contradicted the result of the ANOVA. The interaction between BKB scores and

PCT scores for basal electrodes suggests that participants with above chance scores for basal electrodes on the PCT performed better with the L1U1 map than participants with chance or below chance scores. Results for participants according to PCT scores for basal electrodes are shown in Figure 8.

Figure 8 here

To consider the effects of the upper and lower boundaries separately, a further repeated-measures ANOVA was undertaken, but without the default map. The within-subjects factors were the lower and upper frequency boundaries and the between subjects factors were PCT scores for apical and basal electrodes. A significant main effect of lower frequency boundary was found [$F(1.3,11.7)=6.94$, $p=0.017$]. There was no interaction between the PCT contour score for basal electrodes and BKB sentence score with the different lower frequency boundaries [$F(1.3,11.7)=0.256$, $p>0.05$] and no independent effect of PCT score for basal electrodes [$F(1,9)=1.16$, $p>0.05$]. Neither was there an interaction between PCT score for apical electrodes and BKB score with the different lower frequency boundaries [$F(1.3,11.7)=0.495$, $p>0.05$] and no independent effect of PCT score for apical electrodes [$F(1,9)=0.14$, $p>0.05$]. Pairwise comparisons, with Bonferroni corrections applied, indicated that L1 offered better performance than L0 [$p=0.031$, $r=0.73$] and L2 [$p=0.005$, $r=0.83$], both large effects.

A significant main effect of upper frequency boundary was found [$F(1.25,11.2)=10.74$, $p=0.005$]. There was also a significant interaction between PCT score for basal electrodes and performance on the BKB sentence test with different upper frequency boundaries [$F(1.25,11.2)=7.61$, $p=0.014$]. There was no interaction between PCT score for apical electrodes and performance on the BKB sentence test with different upper frequency boundaries [$F(1.25,11.2)=1.22$, $p>0.05$]. Pairwise comparisons, with Bonferroni corrections applied, indicated that U2 offered poorer performance than U0 [$p=0.016$, $r=0.77$, a large effect]. No significant difference was found between performance with U0 and U1 or between U1 and U2 [$p>0.05$].

Within-subjects contrasts indicated that participants with poor PCT score for basal electrodes performed worse than those with above chance PCT score for basal electrodes for upper boundary U1, when compared to U0 [$F(1,11)=23.1$, $p=0.001$, $r=0.85$], a large effect and also for upper frequency boundary U2, when compared with U0 [$F(1,11)=9.83$, $p=0.012$, $r=0.72$, a large effect], but not for upper frequency boundary U1 when compared with U2 [$F(1,11) = 1.83$, $p>0.05$]. Upper frequency boundaries as a function of PCT score for basal electrodes is shown in figure 9

Figure 9 here

Results for individual participants for the BKB sentence test were also investigated. Critical differences for the BKB sentence test (Martin, 1997) were used to determine if individual differences between default and altered frequency allocations were significant. This showed that twenty-three individual scores with study maps were poorer than scores for the default map, whilst seven scores were significantly better. P2 had particularly poor scores for the most basally shifted maps, as shown in figure 10; this participant had above chance scores on the PCT for electrode pairs E1E2 to E9E10 but chance or below chance scores for E10E11 and E11E12. Additionally, P2's clinical data suggests poorer take-up of electrical stimulation for basal electrodes than for apical electrodes. In P2's everyday map (and all the study maps), comfort levels rise from 17.7 units on E1 to 35.8 charge units on E12; P2's electrical impedances rise from 3.5 kΩ on E7 to 10 kΩ on E10 and 9.7 kΩ on E12).

The study maps offering improved performance on the BKB sentence test were maps L0U2, L1U0, L1U1 and L2U0. Five improved scores were recorded by participants with above chance scores on the PCT for all electrodes; one was recorded for a participant with chance/below chance scores at the apical end and the other was recorded in a participant with chance/below chance scores at both ends of the electrode array.

Figure 10 here

## Discussion

We evaluated the use of the PCT in a group of CI users, to determine the ability of this test to pick up electrode-specific deficits in pitch perception and to determine whether the test could be used to optimise frequency allocation to electrodes. The test was found to be clinically viable with high acceptance and an acceptable time for completion. Results showed striking variability in pitch discrimination (and worse scores as a group) at both basal and apical regions of the electrode array, but uniformly high levels of pitch perception in the mid region. This finding could be due to: poor spiral ganglion cell survival or function, resulting in the same nerve fibres being stimulated by different electrodes (Kalkman et al., 2014); incursion of the electrode array into the scala vestibuli, (Holden et al., 2013); the presence of fibrotic tissue development or ossification (O'Leary et al., 2013); extrusion outside the cochlea (albeit this explanation is far more likely at the basal end of the array). ) Deeply inserted electrodes in a degenerated cochlea may produce a broader excitation pattern and weak place-pitch percept, as stimulation may excite spiral ganglion (SG) cells and axons in the terminal bulb (Schatzer et al., 2014) . Interestingly, contour scores were above chance for electrode pair 2 vs. 3 for all six participants with the (slightly shorter) Flex28 array, but only for three out of seven participants with the standard array, so it may be that reduced length has improved perception for these electrodes. However, it is less clear as to whether poor pitch perception at the basal end could be explained by poor SG cell counts, and more likely that fibrosis or extra-cochlear position may explain these findings. By contrast, for the middle electrodes, most participants achieved ceiling scores. Ceiling effects could be reduced by testing frequencies between the centre frequencies of adjacent electrodes, making the test more difficult.

A further striking finding was the difference between contour and discrimination scores in some cases. For example, P2 has a pitch reversal for electrode pair E10E11, where discrimination is good but contour is very poor, and a pitch confusion for E11E12 where both contour and discrimination scores are at chance level. It is likely that pitch reversals and impaired pitch discrimination relate to different types of current flow anomaly. Interestingly, a higher number of electrodes showed pitch contour errors compared to pitch discrimination errors, suggesting pitch contour may be a more sensitive measure.

There were seven cases of significant acute improvements in performance with non-default frequency allocations. The maps which offered improved performance either had limited shift (L1U0) or shift of one-third of an octave when compared to the L0U0 (most apical) map. For the L1U0 map, the improvement may be due to a reduction in the frequency range assigned to the most apical electrodes. For the other maps, the basal shift and/or the reduction in the frequency range assigned to the apical electrodes may be responsible. Four participants (P4, P5, P8 and P10) obtained benefit from the maps with basal shift of one-third of an octave (averaged over the frequency range). The frequency allocations for these maps intersect around E6. This suggests that participants may have benefitted from a limited amount of basal shift around this point. The centre frequency for the default map on E5 is 855 Hz. The maps L2U0, L1U1 and L0U2 have centre frequencies of 668, 706 and 745 Hz at this point. These frequencies would have moved along the electrode array by one electrode or less. Improvement may be due to these frequencies becoming easier to discriminate. However, this is not obvious from the PCT results, as all these participants had ceiling scores on the test for their middle electrodes.

Contrary to expectations, pitch perception at the basal, rather than apical, end had the greatest effect on optimal choice of frequency allocation. The upper frequency boundary U0 offered better performance than U2. The interaction between performance on the PCT for basal electrodes and BKB sentence scores with different upper frequency boundaries, suggests that this was due to poor pitch perception for some participants, rather than frequency shift or loss of frequency range, as participants with good basal end pitch perception achieved similar scores with both U0 and U2. The lower frequency boundary L1 offered better performance than L0 and L2. Frequency shift was minimal for E2 and E3 with the L1 maps (with frequency range approximately 250 to 400 Hz). For higher frequencies there was some basal shift. L2 maps had the greatest basal shift overall. L0 had smallest shift overall but the largest amount at the apical end. L0 maps also had the greatest loss of frequency range at apical end.

The difference in performance with different maps for the two groups, suggests that performance could be improved by offering different frequency allocations to CI users according to their basal end pitch perception. Those with good pitch perception at the basal end should be offered map L1U0 or L1U1, whereas those with poor basal end pitch perception should be offered the default map or map L1U0. If such a strategy had been employed for the selection of frequency allocation in this group, there would have been a significant improvement in the group's performance overall [$t(12)$, 2-tailed=-3.31, $p$=0.006, $r$=0.69] when compared with offering all participants the default map.

# Conclusions

A novel test of pitch discrimination and ranking, the Pitch Contour Test (PCT) was performed with a group of MED-EL CI users, who were also tested on a sentence test in noise with ten different frequency allocations. The PCT was found to be viable and took less than half an hour for a limited set of electrodes. Results showed higher levels of pitch discrimination and contour perception in mid compared to basal and apical electrodes, with marked inter-subject variability in these regions. The frequency allocations yielding best performance could be predicted by PCT results. In particular, for those with poor pitch perception for basal electrodes, performance was generally poorer for maps with basal shift. It was possible to suggest a strategy for selecting frequency allocation based on PCT scores, which would have improved speech perception performance for the group as a whole. We propose that the PCT gives valuable and clinically viable information on pitch perception in CI users which can aid in device tuning.

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**Table 1: Participant charateristics for experiment 2**

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

Table 2 Electrode Centre Frequencies (Hz) for Maps with 12 Active Electrodes

| | | Electrode | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Map | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Default | 149 | 262 | 408 | 601 | 855 | 1191 | 1638 | 2234 | 3029 | 4091 | 5511 | 7412 |
| L0U0 | 265 | 359 | 487 | 660 | 894 | 1206 | 1638 | 2234 | 3029 | 4091 | 5511 | 7412 |
| L1U0 | 211 | 285 | 386 | 522 | 706 | 955 | 1292 | 1748 | 2366 | 3201 | 4331 | 5863 |
| L2U0 | 171 | 240 | 338 | 475 | 668 | 940 | 1321 | 1858 | 2614 | 3675 | 5169 | 7271 |
| L0U1 | 262 | 348 | 462 | 613 | 813 | 1080 | 1434 | 1903 | 2527 | 3355 | 4454 | 5913 |
| L1U1 | 211 | 285 | 386 | 522 | 706 | 955 | 1292 | 1748 | 2366 | 3201 | 4331 | 5863 |
| L2U1 | 169 | 233 | 321 | 443 | 612 | 844 | 1164 | 1605 | 2214 | 3055 | 4214 | 5816 |
| L0U2 | 259 | 337 | 439 | 572 | 745 | 970 | 1263 | 1645 | 2142 | 2789 | 3632 | 4731 |
| L1U2 | 208 | 276 | 367 | 487 | 647 | 858 | 1139 | 1512 | 2007 | 2664 | 3536 | 4693 |
| L2U2 | 167 | 226 | 306 | 414 | 560 | 758 | 1026 | 1388 | 1878 | 2542 | 3439 | 4654 |

Figure 1. Four alternative choices for the PCT, as shown on the graphical user interface

Figure 2. Frequency allocations for a selection of the maps used in experiment 2 (a) default, L0U0 and L2U2 maps (b) default, L1U0 and L1U1 maps

Figure 3. Summary of PCT results for all participants for all electrode pairs

Figure 4. PCT scores for four individual participants for individual electrode pairs showing (a) excellent scores for all electrode pairs (b) poor pitch perception at the basal end but good pitch perception for other electrodes (c) poor pitch perception at the apical end of the array but good pitch perception for other electrodes (d) poor pitch perception at both ends of the electrode array but good pitch perception in the middle of the array (e) poor pitch perception for one or more of the middle electrodes

Figure 5. Discrimination scores for the PCT for 11 participants with all electrodes active in their maps. The median value is shown as a heavy line. The box represents the range between the 25$^{th}$ and 75$^{th}$ percentiles. Whiskers represent the range of data, unless this extends beyond 1.5*the inter-quartile range from the box, in which case data points are indicated by small circles as outliers.

Figure 6. Contour scores for the PCT for participants with all electrodes active in their maps. The median value is shown as a heavy line. The box represents the range between the 25th and 75th percentiles. Whiskers represent the range of data, unless this extends beyond 1.5*the inter-quartile range from the box, in which case data points are indicated by small circles as outliers.

Figure 7. BKB sentence scores with different maps in experiment 2. Boxes show the mean for each condition and error bars show one standard deviation. Lower frequency boundaries: default = 100 Hz; L0 = 225 Hz, L0 = 225 Hz, L1 = 179 Hz and L2 = 142 Hz; upper frequency boundaries: default = 8500 Hz, U0 = 8500 Hz, U1 = 6746 Hz and U2 = 5353 Hz.

Figure 8. Interaction between contour score for basal electrodes and BKB sentence scores with different maps. Bars represent the mean for each group for each map; error bars represent one standard deviation.

Figure 9. Interaction between contour score for basal electrodes and BKB sentence scores with different upper frequency boundaries. U0 = 8500 Hz, U1 = 6746 Hz, U2 = 5353 Hz

Figure 10. BKB sentence scores for P2. The darker bars indicate maps which offered poorer performance than the default map.