Title

Objective assessment of electrode discrimination with the auditory change complex in adult cochlear implant users.

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Abstract

The spatial auditory change complex (ACC) is a cortical response elicited by a change in place of stimulation. There is growing evidence that it provides a useful objective measure of electrode discrimination in cochlear implant (CI) users. To date, the spatial ACC has only been measured in relatively experienced CI users with one type of device. Early assessment of electrode discrimination could allow auditory stimulation to be optimized during a potentially sensitive period of auditory rehabilitation. In this study we used a direct stimulation paradigm to measure the spatial ACC in both pre- and post-lingually deafened adults. We show that it is feasible to measure the spatial ACC in different CI devices and as early as 1 week after CI switch-on. The spatial ACC has a strong relationship with performance on a behavioural discrimination task and in some cases provides information over and above behavioural testing. We suggest that it may be useful to measure the spatial ACC to guide auditory rehabilitation and improve hearing performance in CI users.

Keywords

Cochlear implant; electrode discrimination; auditory change complex; ACC; electroencephalography; objective measures

Abbreviations

AB, Advanced Bionics; ACC, auditory change complex; ANSD, auditory neuropathy spectrum disorder; BKB, Bamford-Kowal-Bench; CAPT, CHEAR auditory perception test; CI, cochlear implant; EDL, electrode discrimination limen; EEG, electroencephalography; LME, linear mixed effects; PCA, principal component analysis; Hotelling-T2, Hotelling's t-squared; ROI, region of interest

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Declaration of Interest

The authors report no conflicts of interest.

Author contributions

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. RM, JU, GL, PB, AS and DV designed the experiment. DV and JU supervised the project. RM and JU collected and analyzed the data. RM, LM, AS, DKS and DJ recruited participants. RM wrote the manuscript and all the other authors were involved in revising the manuscript.

1. Introduction

Speech processing strategies with cochlear implants (CI) assume that electrodes stimulate distinct populations of neurons in the cochlea in a tonotopic fashion. If electrodes within the CI array are indiscriminable, speech cues will be lost and speech perception may suffer. This has been confirmed by a number of studies which have shown that poor electrode discrimination, particularly in the apical and mid array, is associated with poor speech perception (Busby et al., 2000; Dawson et al., 2000; Henry et al., 2000). Assessment of electrode discrimination ability may be of particular importance, as there is evidence that speech perception in individuals with impaired electrode discrimination, can be improved by deactivating indiscriminable electrodes (Saleh et al., 2013; Zwolan et al., 1997) or by providing auditory training (Fu and Galvin, 2008). Given that there is a sensitive period for auditory development (Holt and Svirsky, 2008; Kral et al., 2006; Nikolopoulos et al., 1999; Sharma et al., 2005), and that auditory experience during this period has large-scale and long-term effects (de Villers-Sidani et al., 2007; Zhang et al., 2001), it follows that interventions to optimize auditory stimulation through the CI should occur as early as possible.

Psychophysical measurements of discrimination depend on attention, cognition and linguistic ability, which limits their use to older children and adults. There has been growing interest in measuring discrimination ability in CI users with the electrically evoked auditory change complex (ACC). This is an auditory cortical potential which occurs in response to a change in an ongoing stimulus. The advantage of electrophysiological measurements is that they do not require active participation and can be performed in young children including infants (Chen and Small, 2015; Martinez et al., 2013). In addition, there is evidence that changes in electrophysiological measurements precede changes in behavioural performance (Tremblay et al., 1998). The ACC may therefore provide information over and above behavioural testing and be particularly suited to assessing whether stimulus change is encoded in the auditory pathway in the early period after CI switch-on.

The ACC to a change in place of the stimulating electrode has been termed the ‘spatial ACC’. There is evidence that the spatial ACC provides a useful measure of behavioural discrimination (He et al., 2014; Hoppe et al., 2010). Hoppe et al. (2010) found a significant but weak correlation between behavioural discrimination d-prime score and spatial ACC amplitude. He at al. (2014) measured the relationship between the spatial ACC and

behavioural discrimination in children with auditory neuropathy spectrum disorder (ANSD). An ACC response was defined as being either present or absent based on amplitude criteria and visual identification of the ACC. Behavioural electrode discrimination was assessed with a 2-alternative forced choice task and a pass was defined as a score of ≥4 out of 6 trials. It must be noted that with these criteria, the binomial probability of achieving a behavioural pass by chance is 34% and a high false positive rate would be expected. Nonetheless, a strong relationship between objective and behavioural measures was found using pass-fail rules.

To date, the spatial ACC has only been measured in relatively experienced CI users and also, only in users of the Cochlear device. For the spatial ACC to be clinically useful it must be measurable in different devices. One of the challenges with measuring auditory cortical responses to long stimuli is the presence of CI artefact, which overlaps the electrophysiological response, and varies between devices and stimulation strategies (Martin, 2007; Viola et al., 2011). In addition, it would be useful to measure the spatial ACC in the early period after CI switch-on. An early assessment of electrode discrimination could help to guide management during a sensitive period of auditory development in children. Even in adults, it would beneficial to use such assessments to optimize hearing performance as soon as possible. Previous studies in children and adults, have shown that cortical responses undergo significant morphological changes during the first 6 months after CI switch-on (Jordan et al., 1997; Pantev, 2005; Ponton and Eggermont, 2001; Purdy et al., 2001; Sharma et al., 2005). Pantev (2005), measured cortical responses to frequency shifts with MEG in two adults with magnet-free CIs. Cortical responses could not be detected in these participants for the first 2-3 months after switch-on. To date, the spatial ACC has not been successfully measured in the early period after CI switch-on and its relationship to behavioural discrimination during this period is therefore unknown.

The main aims of this study were to determine 1) whether the spatial ACC can be measured in individuals with different CI manufacturer's devices 2) whether it is feasible to measure the spatial ACC in pre and post-lingually deafened adults at 1 week after CI switch-on 3) how the spatial ACC is related to behavioural discrimination during this period and 4) whether measures of electrode discrimination are correlated with speech perception. The study consists of two experiments. In the first experiment, the spatial ACC was measured in experienced CI users with two different CI manufacturer's devices. In the second experiment, the spatial ACC was measured in newly implanted CI users.

2. General Methods

2. 1 Participants

There were four participants in experiment 1, all of whom had been using their CI for at least 2 years at the time of testing. Participants ranged in age from 18 to 68 years and had a unilateral implant except for participant P2 who was bilaterally implanted. In this participant, the ear which was subjectively reported as being the better hearing ear was chosen for testing. Two participants had MED-EL devices and the other two had an Advanced Bionics device (AB). Demographic details of study participants are provided in table 1.

For experiment 2, ten different participants were recruited and ranged in age from 42 to 80 years. Three participants had pre-lingual onset of deafness and all the others had post-lingual onset of profound deafness. Since one of the aims of this study was to examine the relationship between electrode discrimination and speech perception, participants with the same device were chosen to reduce the potential variability in outcome measures, that might be caused by differences in the implant and electrode array design such as inter-electrode distance and array length. All participants were unilaterally implanted with an AB device and tested at approximately 1 week after CI switch-on (range 7-14 days). The AB Hifocus Mid-Scala electrode was used in all participants, except for S4 who had a Hifocus 1J electrode. Both arrays have 16 electrode contacts but the Mid-Scala electrode has an active length of 15mm with electrode spacings of 1 mm, whilst the 1J electrode is a lateral wall electrode and has an active length of 17 mm with electrode spacings of ~1.1 mm. Demographic details of participants in experiment 2 are shown in table 2.

Participants in both experiments had full electrode array insertions, and electrode impedances and neural response telemetry thresholds were confirmed to be within normal limits. Participants were recruited from University College London Hospital (UCLH) and Guy's and St Thomas' Hospital, London. The study was approved by the UK National Health Service Research Ethics Committee (reference 14/LO/2076) and the Hospital Research and Development department. The study was also adopted to the National Institute of Health Research portfolio. All participants provided written informed consent prior to testing and received a small payment for taking part in the study.

2.2 Stimuli for ACC measurement

Stimuli were adapted from Brown et al. (2008). The speech processor was bypassed and electrodes were stimulated directly with a monopolar configuration through an interface (RIB2 for MED-EL and BEDCS for AB devices). Stimuli consisted of 800 ms alternating polarity biphasic pulse trains at a rate of 1000 pps with phase duration of 50 us. Stimuli were presented at a rate of 0.51 Hz. When measuring the spatial ACC there was a change in stimulating electrode at the midpoint of the stimulus (see figure 1A). The first electrode will be referred to as the 'reference electrode' and the second electrode will be referred to as the 'test electrode'. The cortical responses elicited by the reference and test electrodes will be referred to as the 'onset response' and the 'ACC' respectively.

2.3 Stimulus intensity and loudness balancing

For each electrode the threshold level was measured with an ascending method of adjustment. Stimulation began at a level which was inaudible and increased in 5 uA steps until participants reported that they could just hear a sound. The threshold level was determined by repeating this procedure until the same value was obtained twice in a row. The most comfortable level for the reference electrode was determined by gradually increasing the stimulation level until participants indicated that the loudness was at point 6 on a 10-point AB loudness chart. This procedure was repeated twice and the average of the two estimates was taken as most comfortable level of the reference electrode.

It is known that that the ACC amplitude is affected by changes in loudness as well as spectrum (Kim et al., 2009; Martin and Boothroyd, 2000). In order to minimize loudness cues when switching the active electrode, the current intensity delivered by each electrode was carefully loudness balanced. A loudness balancing procedure adapted from He et al. (2014) was used. The stimulation level of the test electrode was initially set at the most comfortable level of the reference electrode. The reference and test electrode were then stimulated in sequence separated by a gap of 600ms. The level of the test electrode was adjusted until both stimuli were perceived to have the same loudness. This procedure was repeated a total of three times and the average was used as the loudness balanced most comfortable level for the test electrode. The standard deviation of the three measurements was on average 4.77 uA (range 0-13 uA).

2.4 EEG recording

Responses were recorded using a BioSemi Active Two EEG recording system. Participants wore a cap with 64 channels arranged according to the international 10–20 system. Scalp channels overlying and immediately adjacent to the CI receiver package were not connected (typically 1-5 electrodes). Two additional channels were placed on the left and right mastoid. Eye movements were recorded with right infra-orbital and right lateral canthus channels. Channels voltage offset was typically kept below 20 mV and never exceeded 40 mV. Responses were recorded at a sampling rate of 16,384 Hz at a resolution of 24 bits/sample (31 nV LSB). The cut-off frequency of the internal low-pass filter was 3334 Hz.

There were 300 epochs for each condition and the order of conditions was randomized. Participants were given a break every 10 minutes. During the recording session, participants sat in a comfortable chair in an acoustically isolated sound booth and watched a subtitled film of their choice. Participants were encouraged to sit as still as possible.

2.5 EEG Processing

Recordings were processed off-line using a custom analysis module in Python 2.7. Unconnected EEG electrode and poor EEG electrode contacts were automatically detected and removed from the analysis. Data were down sampled (1000 Hz), band-pass filtered between 2-30 Hz (zero-phase, third-order Butterworth filter) and referenced to the contralateral mastoid. Eye movement and eye blink artefact were removed by means of a standard correlation subtraction. EEG responses were de-noised using spatial filtering (Cheveigné and Simon, 2008; Undurraga et al., 2016) as follows:

1. Epochs from each EEG channel were normalized and submitted to principal component analysis (PCA), where components with negligible power were discarded. The remaining components were normalized to obtain a set of orthonormal vectors.
2. Epochs were submitted to a bias function. The definition of the bias function determined the rotation matrix obtained on a second PCA, and so its definition depends on the particular problem. Since we are primarily interested in removing the DC component of the CI artefact which is larger than the neural response, the bias function was defined as the mean.

3. A second PCA was applied to data resulting from the bias function. This resulted in a rotation matrix biased towards the evoked response instead of unrelated events such as residual eye blinks, heart activity, and other ongoing brain activity.
4. The rotation matrix resulting from step 3 was applied to the rotation matrix obtained in step 1. The resulting components were ordered by decreasing bias score so that they could be divided into artefact components (which were discarded), signal components (which were kept), and noise components (which were also discarded).

CI artefact was identified from individual components obtained in step 4. Each of the components were projected back to the sensor space. A component was considered a CI artefact when the scalp map showed a centroid on the side of the implanted device, the amplitude was large and component activations matched the onset/offset of stimulation (Debener et al., 2008). This was typically the first component (the one with largest power) and in a few cases the second or third component also contained onset/offset artefacts.

Per-channel time averages were obtained by applying a weighted averaging method (Don and Elberling, 1994). This method estimates the variance of the noise by tracking one or several fixed points over time from a given subset of consecutive epochs. In this study, the power of the residual noise was estimated by tracking 256 isochronal points (7.5 ms), from a subset of at least five epochs. The final size was determined adaptively by comparing the variance of successive subsets (Silva, 2009). As the variance of each subset is known, the final average is obtained by weighting each subset by the inverse of its variance.

The presence or absence of the ACC was determined objectively by means of a Hotelling's t-squared (Hotelling-T2) test (Golding et al., 2009) which is a multi-dimensional equivalent of the (squared) univariate t-statistic. In this context, the EEG data can be considered as a multivariate measure, i.e. several samples along a region of interest (ROI) which encompasses the waveform region where the response is expected. The samples submitted to the Hotelling-T2 were chosen as in Golding et al. (2009). That is, within a given ROI and for each epoch, several sample bins were determined by averaging samples every 40 ms. A typical ROI had a length of 200 ms, between 450 – 650 ms after stimulus onset for the ACC response. This time window was chosen as it typically encompasses the P1, N1 and P2 peaks of the ACC. This led to a total of about 5 bins per epoch - equivalent to having 5 variables per epoch. These 5 variables - sampled 300 times each - were submitted to the Hotelling-T2

test which tested probability that any linear combination of the 5 variables had a mean value significantly different from zero. For experiment 2, the ROI time window was adjusted in 4/40 cases, to 450 – 700 ms after stimulus onset, due to a late P2 component. An objective ACC pass for an electrode pair was defined as a Hotelling-T2 p value < 0.05 at > 4/9 frontal and central scalp channels (Cz , C1, C2, Fz, F1, F2, FCz, FC1 and FC2; C = central, F = frontal, FC = fronto-central; suffix z represents midline location, 1 represents location to the left of midline and 2 represents location to the right of midline).

An automatic peak detection algorithm was used to identify evoked response peak amplitude and latency. P1 was defined as the maximum peak voltage between 30-90ms for the onset response and between 430 and 490 ms for the ACC. N1 was defined as the minimum peak voltage between 70 and 150 ms for the onset response and between 470 and 550 ms for the ACC. P2 was defined as the maximum positive peak voltage occurring between 150 and 290ms for the onset response and 550 and 690 ms for the ACC. Although the Hotelling-T2 was used to determine whether the ACC was present or absent, the magnitude of the response was quantified by measuring peak amplitude. Data are presented at the scalp location FCz unless otherwise stated as the magnitude of the ACC is typically largest at this site. In experiment 1, average scalp responses are also presented as these provide an estimate of the magnitude of CI artefact across the scalp.

2.6 Statistical analysis

All statistical analyses were performed using the R software package (R Development Core Team, 2015). Linear mixed-effects (LME) models were used to analyze datasets with repeated measurements as they allow complex modelling of random effects and can deal with unbalanced data (Baayen et al., 2008; Bates et al., 2015). The factor ‘subject’ was set as a random effect in these models. For across subject analysis of speech perception, multiple linear regression was used. In both cases, backward stepwise reduction was used to optimize the model. Visual inspection of residuals and Cook’s distance calculation were used to identify outliers and influential data points.

3. Experiment 1: Pilot phase - assessment and removal of CI artefact

3.1 Design and Methods

The aim of this experiment was to determine the feasibility of measuring the spatial ACC in AB and MED-EL devices. In each participant, the reference electrode was chosen from the middle of the array. The reference electrode was paired with an adjacent test electrode, which was described by the participant as clearly having a different pitch. Electrode pairings are shown in table 1. There were three stimulation conditions as shown in figure 1. The reference electrode is shown in blue and test electrode in red. In the 'suprathreshold change' condition (fig 1A) the reference electrode was stimulated for 400ms followed by the test electrode for another 400ms with no gap. Stimulation level was at the most comfortable level as determined by the loudness balancing procedure described earlier. In addition, there were two control conditions. The first control consisted of a 'suprathreshold no change' condition (fig1B) in which the reference electrode was stimulated for 800ms at the most comfortable level. This condition was included to evaluate the effect of radiofrequency or switch artefacts on the recordings, as the processors were still programmed to "switch" to the same electrode at 400 ms. The second control was the 'subthreshold change' condition (fig 1C), in which stimulation level was at 10 uA below the threshold level for both test and reference electrodes. By measuring the ACC in a subthreshold stimulation condition, the CI artefact can be measured accurately and compared to artefact isolated with signal processing techniques in suprathreshold stimulation conditions. The order of presentation of conditions was randomized. The total experimental time was 1.5 hours.

3.2 Results

3.2.1 Assessment of CI artefact

The CI related artefact varied between participants. Participants P1 and P3 had large CI related artefacts which could be isolated with spatial filtering. The first components of spatial filtering for the 'subthreshold change' condition and 'suprathreshold change' condition are shown in figure 2. This component has an onset and offset which corresponds to the duration of electrical stimulation and represents CI DC artefact. Scalp voltage maps show the location of CI artefact on the side of the CI device. The scalp artefact was predominantly in the midline in participant P1 but also extended to the side of the CI. In participant P3, artefact was predominantly at lateral scalp channels on the side of the CI. In neither case was there

visible artefact on the contralateral scalp channels in any of the stimulation conditions. A switch artefact, associated with changing the stimulating electrode was present in the 'suprathreshold change' and 'subthreshold change' conditions, but not the 'no change' condition. In participants P2 and P4, who both had MED-EL devices, CI artefact was comparatively much smaller and did not affect the ACC.

As can be seen in figure 2, the CI artefact isolated in the 'subthreshold change' condition and 'suprathreshold change' condition are similar in morphology.[1] Figure 3 shows that spatial filtering can be used to effectively remove CI artefact in the suprathreshold change condition. The average scalp response is shown before CI artefact removal in figure 3A. After removing the first component of spatial filtering (shown in figure 2B), the onset response and ACC can be clearly identified.

3.2.2 ACC in the test and control conditions

In all four participants, Hotelling-T2 indicated that the ACC was present in the suprathreshold change condition but absent in the two control conditions. An example of responses from the three stimulation condition in participant P4 is shown in figure 4. Figure 5 shows the N1-P2 peak amplitude of the onset and ACC response for the three stimulation condition in all 4 participants. A linear mixed-effects analysis of the relationship between N1-P2 amplitude and stimulation condition across scalp channels was performed. The dependent variable was the N1-P2 amplitude. Fixed effects included 'condition' (suprathreshold change, subthreshold change and no change), 'scalp channel' (Cz, C1, C2, FCz, FC1, FC2, Fz, F1, and F2) and 'peak type' (onset response or ACC). The interaction term for 'condition' and 'peak type' was included in the model as well. The factor 'scalp channel' was removed from the model as it was not significant ($F(8, 199) = 0.91$, $p = 0.51$). Analysis of variance of the reduced model showed that there was a significant effect of 'condition' ($F(2,207) = 694$, $p < 0.001$), 'peak type' ($F(1,207) = 241$, $p < 0.001$) and the interaction between 'condition' and 'peak type' ($F(2,207) = 118$, $p < 0.001$).

Post-hoc comparison of the three conditions for each peak type was conducted using a Bonferroni adjusted alpha level of 0.0083 (six comparisons). This showed that for the ACC,

[1] In participant P1, the artefact in the subthreshold change condition is larger in amplitude than the suprathreshold change condition. The DC artefact is due to impedance mismatch, is unrelated to stimulation level and can occasionally change during a testing session.

there was a significant difference between the N1-P2 amplitude in the suprathreshold change condition and both control conditions ($p < 0.001$) but no significant difference between the two control conditions ($p = 0.1$). For the onset response, N1-P2 amplitude was significantly different between all 3 conditions ($p < 0.001$). In the no change condition, the same population of neurons are stimulated for twice as long as in the suprathreshold change condition in each trial and neural adaptation may account for the smaller onset response in this condition.

4. Experiment 2: Measurement of ACC at 1 week after switch-on

4.1 Design and Methods

The main aim of this experiment was to determine whether it is possible to measure the spatial ACC soon after CI switch-on and how this measurement relates to behavioural electrode discrimination. A secondary aim was to determine whether objective electrode discrimination (measured with the ACC) and behavioural electrode discrimination are related to speech perception at this early stage.

Only the suprathreshold change condition was used in this experiment and the electrode pairs 1-2, 2-3, 3-4 and 4-5 were tested. These are the apical most electrodes in the AB device and typically encode frequencies of 250-828 Hz. These electrodes encode the first formant of vowels and previous studies have shown that the apical electrodes are important for speech perception (Busby et al., 2000; Geier and Norton, 1992; Henry et al., 2000). Loudness balancing was performed as described earlier. Electrode 3 was chosen as the initial reference electrode as it lies in the centre of the five electrodes chosen for testing. The most comfortable level of electrode 3 was determined and adjacent electrode pairs were loudness balanced in the following order: electrode 4 with electrode 3, electrode 5 with electrode 4, electrode 2 with electrode 3 and electrode 1 with electrode 2.

4.1.1 Behavioural electrode discrimination

Behavioural electrode discrimination was determined using a 3-interval 2-alternative forced choice paradigm. The first interval always contained the reference electrode stimulus and the test electrode stimulus occurred with equal probability in either the second or third interval. Participants were instructed to choose the interval which was different. Feedback was not provided. Stimuli were identical to those used in EEG recordings: alternating polarity

biphasic pulse trains from a single electrode, with pulse rate of 1000 pps, phase width of 50us and duration of 400ms. Each interval was 1.4 s long. There were a total of 20 trials per electrode pair. A behavioural pass was defined as a score of at least 80%. This cut-off was chosen as it has a binomial probability of <0.01 and reduces the likelihood of a false positive pass. In addition, from a clinical point of view, a high cut off might be more relevant as performance could potentially be improved by addressing electrodes with lower discrimination scores. The behavioural score was converted to a d-prime score. The maximum d-prime score was 2.77 based on a correction factor for a score of 100% (Stanislaw and Todorov, 1999).

4.1.2 Speech perception testing

Sentence and vowel perception testing was performed in a sound treated booth using the AB-York Crescent of Sound (Kitterick et al., 2011). In both cases, no feedback was provided and a single presentation of the test material was allowed during each trial. Participants used their own processor with their preferred CI map and the non-CI ear was unaided. Open-set sentence perception was tested with the Bamford-Kowal-Bench (BKB) test. Listeners were asked to repeat each sentence and were given a score based on the number of key words correct. Two lists of 16 sentences (100 words) were chosen randomly for testing. Presentation level was 70 dBA in quiet.

Closed-set vowel perception was tested with the CHEAR Auditory Perception Test (CAPT) vowel sub-test. The CAPT was used because it is sensitive to spectral differences in hearing aid fitting algorithms (Marriage et al., 2011). The CAPT is a four-alternative-forced-choice monosyllabic word-discrimination test spoken by a female British English speaker. It contains five sets of four minimally-contrastive real words e.g. cat, cot, cut, cart. Listeners were asked to respond by choosing from four pictures on a computer screen. Stimuli were presented at 60 dBA in quiet. The test was repeated to give a total score out of 40. This was converted to a d-prime score with a maximum of 3.69 (Stanislaw and Todorov, 1999).

None of the participants had significant residual hearing in the contralateral ear except for participant S10 (see table 2). It is unlikely that hearing from the contralateral ear affected this participant's speech scores as his unaided (ie no CI or hearing aid) BKB sentence score was 0%. EEG and speech testing were done in a single session which lasted approximately 2.5 hours including breaks.

4.2 Results

4.2.1 Characteristics of the ACC

The presence or absence of the spatial ACC was defined based on Hotelling-T2 criteria as described in the general methods. The number of electrode pairs that elicited an ACC ranged from 0-4 in each participant as shown in table 3. The ACC response morphology was similar to that of the onset response and typically consisted of the P1-N1-P2 complex. Table 4 shows the peak latencies and amplitudes of the onset and ACC responses, for recordings where there was an objective ACC pass. The peak latencies of P1, N1 and P2 components of the ACC response were significantly longer than that of the onset response (two-tailed paired t-test $p < 0.001$). In addition, N1-P2 amplitude of the ACC was significantly smaller than that of the onset response (paired t-test, $p < 0.001$).

4.2.2 Relationship between behavioural discrimination and the ACC

4.2.2.1 Relationship using pass-fail criteria

The relationship between behavioural discrimination and the spatial ACC was assessed using pass-fail rules. Briefly, a behavioural pass was defined as a score of ≥ 80% on behavioural testing, and an objective pass required a significant response (Hotelling-T2 p value < 0.05) at > 4/9 frontal and central scalp channels. There was agreement between objective and behavioural measures in 35/40 cases: there were 15 electrode pairs with a behavioural fail and objective fail, 20 electrodes pairs with a behavioural pass and objective pass, 3 electrode pairs with a behavioural fail and objective pass and 2 electrode pair with a behavioural pass and objective fail. There was significant agreement between objective and behavioural measurements (Cohen's kappa = 0.75, $p<0.001$). Figure 6 shows an example of cortical responses in participant S1. This shows that in the same participant, the ACC is absent for an electrode pair with a behavioural fail (fig 6A) but is clearly present for an electrode pair with a behavioural pass (fig 6B).

The relationship between the ACC and behavioural measurements can be further examined according to deafness onset. For the seven post-lingually deafened adults, there was agreement between objective and behavioural electrode discrimination for all 28 electrode pairs. For the pre-lingually deafened adults, there was agreement between objective and behavioural discrimination, for 7 out of 12 electrode pairs. There were only two cases from

the same participant (S4) with a behavioural pass but objective fail . This participant had small ACC responses across all four electrode pairs (range 0.08 - 1.26 uV). The 3 electrode pairs with an objective pass but behavioural fail were from the 3 pre-lingually deafened adults (participants S2, S4 and S7) and are shown in figure 7. Of note, electrode pair 2-3 in participant S2 (fig 7A) had a discrimination score of only 45% but a large ACC amplitude (4.60 uV). These data suggest that an ACC response may be present in the absence of accurate behavioural discrimination.

4.2.2.2 Mixed model analysis of relationship between N1-P2 peak amplitude and behavioural discrimination

There appears to be a strong relationship between the ACC and electrode discrimination when using pass-fail rules, especially in post-lingually deafened adults. We next examined the relationship between the ACC amplitude and behavioural discrimination. A behavioural pass was set at a score of 80% a priori, but it is possible that the ACC is encoded at lower levels of behavioural discrimination. The aim of this analysis therefore, was to determine whether electrode-pairs with intermediate discrimination scores (e.g. 70%) had larger ACC amplitudes than those with discrimination scores around chance (e.g. 50%). Electrode pairs were divided into three categories based on behavioural discrimination score: 'poor' (score < 60%), 'intermediate' (score 60 - 79%) and 'good' (score ≥ 80%). Categories of behavioural discrimination were used due to the small number of participants in this study. Figure 8 shows the ACC N1-P2 amplitude according to behavioural discrimination category.

A linear mixed-effects model was used to examine the relationship between N1-P2 amplitude and behavioural discrimination category. The N1-P2 peak amplitude was modelled with fixed factors 'behavioural category' (poor, intermediate or good), 'deafness onset' (pre-lingual or post-lingual) and 'electrode pair' (1-2, 2-3, 3-4 or 4-5). The interaction term for 'deafness onset' and 'behavioural category' was also included in the model. The factor 'electrode pair' was eliminated from the model as it was not significant ($F(3, 24) = 1.28$, $p = 0.30$). Analysis of variance of the reduced model revealed a significant effect of 'behavioural category' ($F(2, 31) = 5.01$, $p = 0.013$) and the interaction between 'deafness onset' and 'behavioural category' ($F(2, 31) = 3.39$, $p = 0.047$).

Post-hoc comparison of the three behavioural categories, within the post and pre-linguals groups was conducted using a Bonferroni adjusted alpha level of 0.0083 (six comparisons).

This showed that in post-lingually deafened individuals, there was a significant difference in amplitude between the good and poor groups ($p = 0.005$) and the good and intermediate groups ($p < 0.001$). However, there was no significant amplitude difference between the poor and intermediate groups ($p = 0.67$). For the pre-lingually deafened individuals the number of data points is small and there was no significant difference in amplitude between the poor, intermediate or good groups ($p > 0.10$ for all comparisons).

These data show that in post-lingually deafened adults, only high levels of behavioural discrimination performance are associated with a spatial ACC response. In pre-lingually deafened adults, there does not appear to be a strong relationship between ACC amplitude and behavioural discrimination.

4.2.2.3 Non-monotonic relationship between N1-P2 amplitude and behavioural discrimination in post-lingually deafened adults

In post-lingually deafened adults, there appears to be a strong relationship between the ACC N1-P2 amplitude and behavioural discrimination. If there was a monotonic relationship between behavioural discrimination and ACC amplitude, then within a participant, larger behavioural discrimination score would be associated with larger amplitude ACC responses for 'good' electrode pairs. There were only two participants who had more than 1 electrode pair in the 'good category' which were not all at the ceiling level of behavioural discrimination. As seen in table 5, even for electrode pairs in the 'good category', higher discrimination scores within a participant are not necessarily associated with larger ACC amplitudes. This suggests that there is a non-monotonic relationship between ACC amplitude and behavioural discrimination.

4.2.3 Relationship between electrode discrimination and speech perception

4.2.3.1 Behavioural electrode discrimination and speech perception

Electrode discrimination scores for each participant were collapsed to the mean behavioural d-prime across the 4 electrode pairs. The mean d-prime score was used as this provides a measures of discrimination ability across the apical region of the cochlea. There was a significant correlation between mean behavioural electrode discrimination d-prime and vowel score d-prime ($r = 0.68$, $p = 0.032$) and BKB sentence score ($r = 0.73$, $p = 0.016$). This relationship is shown graphically in figure 9. As the distribution of BKB scores was non-

normal, the relationship with the mean d-prime score was also examined with Spearman's rank correlation coefficient. This showed a trend towards significant correlation (rho = 0.63, p = 0.052).

Differences in speech perception scores between participants could be accounted for by factors other than electrode discrimination ability. We therefore conducted a backward stepwise regression analysis, in which speech perception score was the dependent variable, and 'deafness onset' (pre-lingual or post-lingual), 'duration of bilateral profound hearing loss' and 'mean electrode discrimination d-prime' were included as independent factors. There was no evidence of significant collinearity between independent factors. Both vowel and sentence perception scores were best modelled with 'mean electrode discrimination d-prime' alone which was a significant predictor of speech perception score. The model accounted for 46% of the variance in vowel scores ($F(1, 8) = 6.73$, $p = 0.032$) and 53% of the variance in sentence scores ($F(1, 8) = 9.16$, $p = 0.016$).

4.2.3.2 The spatial ACC and speech perception

An objective discrimination score was calculated for each participant by taking the mean of the ACC N1-P2 peak amplitude across the 4 electrode pairs. There was no significant correlation between the objective discrimination score and vowel perception score ($r = 0.37$, $p = 0.30$) or sentence perception scores ($r = 0.18$, $p = 0.62$). The relationship between the number of discriminable electrode pairs defined using objective pass-fail criteria and speech perception was examined with Spearman's rank correlation coefficient. This also showed no significant correlation with vowel (rho=0.54, p=0.10) or sentence perception scores (rho = 0.42, p = 0.22). Since the relationship between the spatial ACC and behavioural discrimination is not as robust in pre-lingually deafened adults, the analysis was repeated in post-lingually deafened adults alone and this showed a similar pattern of results (supplementary table 1).

5. Discussion

We have shown that it is possible to measure the spatial ACC in different CI devices and as early as 1 week after switch-on. The sample size in both experiments is small which may limit the statistical analysis. Nonetheless, these data indicate that there is a strong relationship between the spatial ACC and behavioural measures of electrode discrimination. Furthermore in certain cases the ACC could be recorded in the absence of accurate behavioural

discrimination. This suggests that the spatial ACC reflects encoding of stimulus change at the level of the auditory cortex and is not necessarily related to the perception of change itself.

5.1 Assessment and removal of CI artefact

The size and distribution of artefact varies between individuals and device. In both experiments, we found that the CI artefact was usually limited to the side of the implant and was never present on the contralateral side. He et al. (2014) and Scheperle and Abbas (2015) showed that it was feasible to measure the ACC using 1-2 midline scalp channels in the Cochlear device. Our data suggest that such an approach, with few scalp channels, could be used in other CI devices provided artefact free locations are selected.

The advantage of multi-channel scalp recordings is that CI artefact can be removed allowing assessment of cortical responses at a greater number of locations as well as source localization which we are exploring for future studies. A number of techniques have been used to remove CI artefact (Debener et al., 2008; Martin, 2007; Mc Laughlin et al., 2013). We found that spatial filtering was an effective technique which usually isolates DC artefact in 1-2 components which makes artefact identification simpler and quicker. In addition, the artefact isolated by spatial filtering in the suprathreshold stimulation condition was similar to that in the subthreshold stimulation condition. This implies that the neural response is unlikely to be significantly affected by artefact removal with this technique.

5.2 Characteristics of the spatial ACC at 1 week after switch-on

In keeping with other studies (Brown et al., 2008; He et al., 2014; Scheperle and Abbas, 2015), we found that the spatial ACC morphology was similar to that of the onset response and was dominated by N1 and P2 components. He et al. (2014) showed that the ACC in children with auditory neuropathy is often characterized by P1 and N2 peaks. This may be a sign of auditory immaturity and this morphology was not observed in any of our participants including pre-lingually deafened adults. Similar to other studies (Brown et al., 2008; He et al., 2014; Martin and Boothroyd, 1999), we found that the amplitude of the ACC is significantly smaller than that of the onset response. In addition, peak latencies of the P1, N1 and P2 components of the spatial ACC were significantly later than that of the onset response. Other studies have reported ACC peak latency being later (He et al., 2012; Martin and Boothroyd, 1999), no different (Brown et al., 2008; He et al., 2012) or even earlier (Kim

et al., 2009) than the onset response peak latency. This may relate to the different stimuli used in these studies.

5.3 Relationship between the spatial ACC and behavioural discrimination

5.3.1 Relationship in post-lingually deafened adults

There was a strong relationship between the ACC and behavioural discrimination performance in post-lingually deafened adults. The ACC could be used to predict a behavioural pass/fail accurately in 28/28 electrode pairs in 7 adult participants. A number of other studies have reported a strong relationship between objective ACC and behavioural measures of electrode discrimination. He et al. (2014) found a perfect relationship between the spatial ACC and behavioural measurements in CI children with auditory neuropathy. Presence of the ACC was determined based on visual identification of a response as well as minimum amplitude criteria. Behavioural discrimination was tested with a 2-alternative forced choice task and a pass was defined as a score of $\geq 4/6$. According to binomial probability, with these criteria, a pass could have been achieved by chance in 34% of cases. We chose to use stricter behavioural criteria in our study in order to reduce the false hit rate. Hoppe et al. (2010), reported that the ACC could be measured in 88% of cases in which participants could successfully discriminate electrodes. In this study, the criteria for assessing whether the ACC was present or absent were not defined.

The within subject analysis, showed that only high behavioural discrimination scores are associated with a spatial ACC. However, electrode pairs with intermediate discrimination scores, between 60-80%, did not have significantly different amplitudes to electrode pairs with scores at or around chance level (<60%). This finding is in keeping with other studies, which have examined the relationship between the ACC and behavioural performance in normal hearing individuals (He et al., 2012; Michalewski et al., 2005). In the study by He et al. (2012), behavioural threshold for frequency discrimination was determined with an adaptive procedure estimating 70.7% correct detection. It was found that the ACC threshold was significantly higher than the behavioural threshold suggesting that in general, only behavioural scores greater than 70.7% are associated with an ACC response. Presumably at lower levels of behavioural performance, stimulus change is encoded less reliably in the auditory pathway and there are limits to the sensitivity of recording far-field responses related to the stimulation paradigm and the technique itself.

Our data suggests that there is a non-monotonic relationship between ACC amplitude and behavioural discrimination. We found that within subjects, electrode pairs with the highest behavioural discrimination scores did not necessarily have the largest ACC amplitude. Other studies have found a non-monotonic relationship between spatial ACC amplitude and electrode separation in CI users (He et al., 2014; Scheperle and Abbas, 2015). The reason for this may be because different electrode locations and therefore, different dipole locations are being compared. It may also be because the ACC is not directly related to the perception of stimulus change. The onset N1 component is associated with encoding and detection of a threshold-level auditory stimulus (Näätänen and Picton, 1987; Parasuraman et al., 1982). The presence of the ACC may therefore signify that a stimulus change above a certain threshold has occurred but the amplitude may not be related to strength of perception.

5.3.2 Relationship in pre-lingually deafened adults

To the best of our knowledge this is the first study to examine the relationship between behavioural discrimination and the ACC in pre-lingually deafened adults. The spatial ACC could be used to predict behavioural discrimination accurately in 7/12 electrode pairs in 3 adult participants. In addition, the mixed model analysis, showed that ACC amplitude did not differ significantly between electrode pairs with 'good, 'intermediate' or 'poor' discrimination scores. Given the small sample size, these results must be interpreted with caution and should be considered preliminary in nature. However, our data suggests that the spatial ACC is a less reliable measure of behavioural discrimination in pre-lingually deafened adults compared to those with post-lingual deafness onset. There were two electrode pairs from the same participant which had an objective fail but behavioural pass. All of the responses for this participant were small. It may be possible to improve the sensitivity and efficiency of ACC measurements by optimizing the stimulation paradigm (Martin et al., 2010; Näätänen and Picton, 1987).

An interesting finding in this study is that in all 3 pre-lingually deafened adults, the spatial ACC could be recorded in the absence of accurate behavioural discrimination. There could be a number of explanations for this. Firstly, it could be argued that the ACC occurred due to a perceived change in loudness if the electrode pairs were not loudness balanced properly. However, this is unlikely, as in the behavioural task, participants were instructed to choose the sound which was different; if there were loudness cues, then higher behavioral scores would be expected in these individuals. Secondly, it could be that the threshold of 80% for a

behavioural pass (binomial probability < 1%) was too high. Even if a pass was defined as a score of ≥ 75% (binomial probability < 5%) these electrodes pairs still would have a behavioural fail. In addition, one participant had a discrimination score below chance level but had a large ACC amplitude. It is also noteworthy, that in the mixed model analysis of ACC amplitude there was no significant difference between the poor and intermediate behavioural discrimination categories in pre- and post-lingually deafened adults. This suggests that threshold of 80% for a behavioural pass is appropriate for this experimental paradigm.

It therefore appears, that in certain individuals, the change in stimulating electrode is encoded at the level of the auditory cortex but not perceived accurately. Tremblay et al. (1998) measured mismatch negativity and behavioural discrimination after training participants to discriminate stimuli which differed in voice onset time. Four out of ten participants showed significant changes in MMN prior to changes in identification ability. After CI switch-on, patients undergo active and passive learning, gained through auditory experience with their CI. There is evidence that learning induces different neurophysiological changes which underlie fast and slow phases of learning (Atienza, 2002). The presence of the ACC in our participants may therefore indicate that that they have the potential to develop behavioural discrimination at a later stage. Another possible explanation for the failure to perceive an encoded stimulus is abnormal connectivity of the auditory cortex of congenitally deafened individuals. It has been proposed that congenital deafness can lead to functional decoupling of the primary and secondary auditory cortex (Kral and Sharma, 2012). There is evidence of abnormal patterns of auditory activation in congenitally deaf individuals (Gilley et al., 2008; Naito et al., 1997). Truy et al. (1995) showed that in a pre-lingually deaf individual, the auditory cortex could be activated by electrical stimulation of the cochlea in the absence of the sensation of sound.

Taken together, these results suggest that the ACC represents cortical encoding of stimulus change; whilst this encoding is usually associated with change detection, this may not be the case in the early stages of learning or in an auditory cortex which has failed to develop normally due to auditory deprivation.

5.4 Reasons for poor electrode discrimination

Apical electrode discrimination ability varied widely, both amongst pre- and post-lingually

deafened individuals in our study. In the main, this is likely to be due to peripheral factors including electrode placement, current spread and spiral ganglion survival (Long et al., 2014; Pfingst et al., 1985). Electrode discrimination is affected by stimulus intensity in CI users (Pfingst et al., 1999). Although electrodes were tested at the most comfortable level in our study, it is possible that differences in stimulation levels/perceived loudness could have affected electrode discrimination scores as well as the ACC. Another factor that might contribute to electrode discrimination ability is the tonotopic organization of the auditory cortex. Studies in both animals and humans have shown that hearing loss is associated with expanded cortical representation of lesion edge frequencies (Dietrich et al., 2001; Rajan et al., 1993). Following CI, it is therefore possible that electrodes will activate overlapping cortical regions. Studies in neonatally deafened cats have shown that tonotopic organization in the auditory cortex can, at least partially, be restored by chronically stimulating the auditory pathway with a CI (Fallon et al., 2009). Therefore, it is expected that in some participants, pitch perception and electrode discrimination will improve with CI experience.

5.5 Electrode discrimination and speech perception

We found that mean electrode discrimination d-prime scores were correlated with open-set and closed-set speech perception. Apical electrodes encode low frequencies which provide important cues for speech perception (Li and Loizou, 2008). In our study, mean apical electrode discrimination d-prime was the strongest predictor of speech perception even after taking into account deafness onset and duration of bilateral profound hearing loss. Although the sample size is small, these results are in keeping with Dawson et al. (2000) and Busby et al. (2000) who found that apical EDLs were negatively correlated with closed-set speech perception. Busby et al. (2000) did not find a relationship between EDL and open-set speech perception. This may be because in the study by Busby et al. (2000), apical EDLs were measured around a single electrode, whereas in our study electrode discrimination ability was measured across multiple electrode pairs.

We did not find a correlation between spatial ACC and speech perception even after excluding pre-lingually deafened individuals. The study was underpowered for this analysis and the significance levels must be interpreted with caution. The poor correlation between ACC amplitude and speech perception is likely due to large inter-subject variability in ACC amplitude. This variability has been observed in other studies of normal hearing and CI populations (Brown et al., 2008; He et al., 2014, 2012). In the study by He et al. (2012), the

ACC amplitude elicited by a change in frequency of 100Hz, varied from 1.51 to 6.85uV in normal hearing individuals. This variability is likely to be a result of differences in cortical folding and resultant dipole orientations. Scheperle and Abbas (2015) however found a significant correlation between mean spatial ACC amplitude and speech perception with an experimental map. In this study however, the ACC amplitude was not measured but rather was estimated from electrically evoked compound action potential (ECAP) separation indices. He et al. (2014) found that mid-array EDL, as measured with the spatial ACC, could be used to predict speech performance, when categorized as good or poor, in children with auditory neuropathy. We found that correlations coefficients for the number of discriminable apical electrodes and speech perception were quite high though they did not reach statistical significance. It therefore may be more relevant to use the spatial ACC to define whether an electrode change is encoded or not, rather than measuring the absolute response amplitude.

5.6 Clinical implications

During early childhood, children are in a sensitive period of auditory development. It is therefore important to optimize stimulation through the CI. Objective measurements such as the ACC may be particularly useful in children in whom behavioural testing is not possible. Poor electrode function can be managed with a number of different strategies which have been shown to improve speech perception - these include deactivation of indiscriminable electrodes (Garadat et al., 2013; Saleh et al., 2013; Zwolan et al., 1997), site specific mapping strategies (Zhou and Pfingst, 2014) and auditory training (Fu and Galvin, 2008).

In older children and adults, it may be useful to measure the spatial ACC in conjunction with behavioural testing. If behavioural discrimination is poor but a spatial ACC response is present, implying that the stimulus change is encoded, auditory training may be the most appropriate management strategy. Fu and Galvin (2008), reported that auditory training resulted in large improvement in behavioural d-prime scores in a pre-lingually deafened adult and this was associated with an improvement in vowel and consonant recognition. Further work is needed to determine the amount of performance gain that can be obtained with training in these populations.

To make the ACC clinically feasible, recording time must be reduced. Martin et al. (2010), showed that the efficiency of ACC recordings could be increased by using alternating stimuli without a silent interval. The set-up time could also be reduced by using fewer scalp channels

to record cortical responses as discussed earlier. In this and other studies (He et al., 2014; Scheperle and Abbas, 2015) a loudness balancing procedure was used to reduce the effect of loudness cues on spatial ACC measurements. A technique for loudness balancing without behavioural feedback is needed to measure the spatial ACC accurately in young children. One approach would be to randomly vary stimulus level around estimated comfort levels. It may also be possible to use objective measurements to perform loudness balancing (Van Eeckhoutte et al., 2016) and this warrants further investigation.

6. Conclusion

We have shown that the spatial ACC can be measured in different CI devices and at an early stage after CI switch-on. It will be important to understand how the ACC develops in relation to behavioural discrimination and a study to determine this is currently on-going in our lab. The spatial ACC represents encoding of stimulus change at the level of the cortex and can provide information over and above behavioural testing. This raises the possibility of using this objective measure to guide management at an early, and potentially critical period of auditory rehabilitation.

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Figures

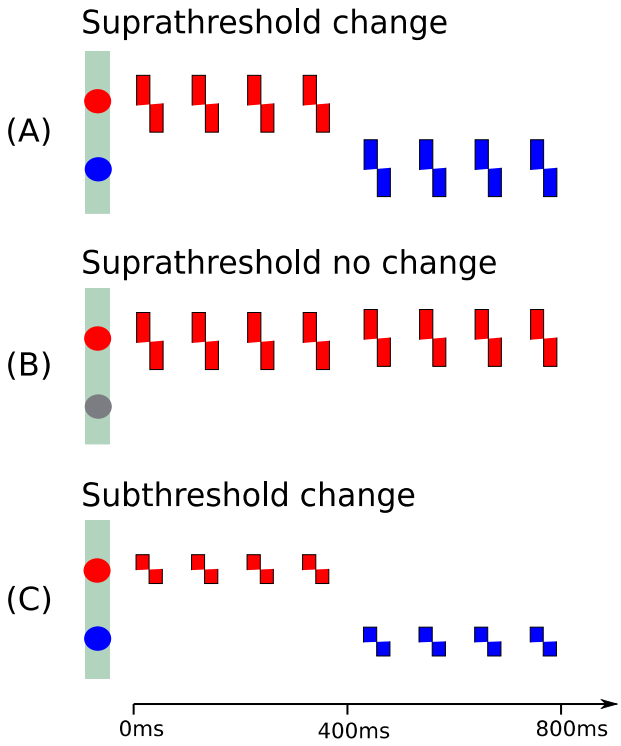

Figure 1. Schematic of the stimuli used for direct electrical stimulation of the CI. Stimuli consisted of 800ms biphasic electrical pulses at 1000 pulses per second. The test electrode is shown in blue and and the reference electrode is shown in red. (A) In the suprathreshold change condition, there was a change in stimulating electrode at 400ms. Stimulation was at the loudness balanced most comfortable level. (B) In the suprathreshold no change condition, the reference electrode was stimulated continuously for 800ms at the most comfortable level. (C) In the subthreshold change condition, there was a change in stimulating electrode at 400ms. Stimulation was at 10 uA below threshold for the reference and test electrodes. This condition was included to measure CI artefact.

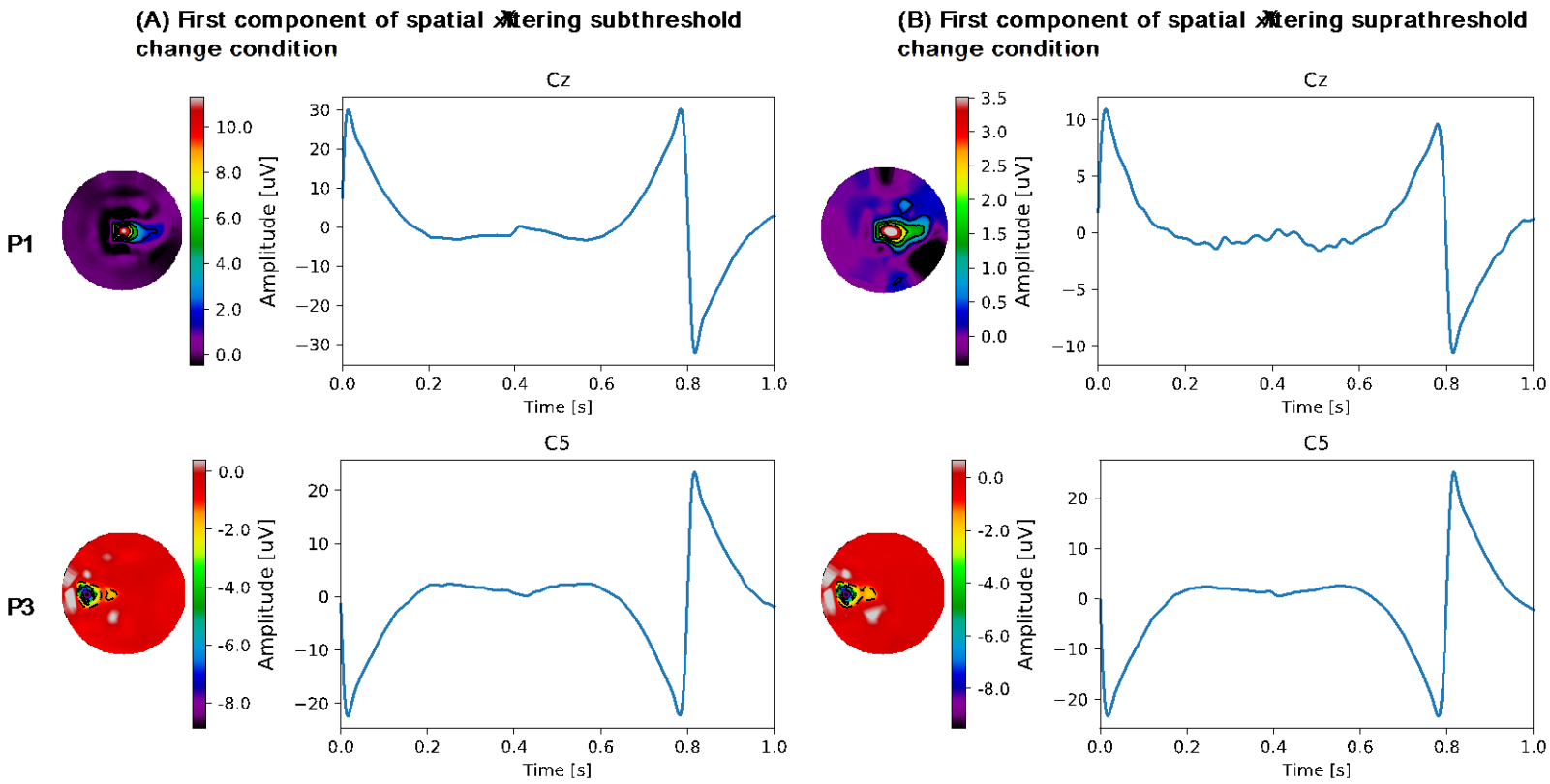

Figure 2. Scalp voltage maps and time course for the first component of spatial filtering in participants P1 and P3 in the subthreshold change condition (A) and suprathreshold change condition (B). Time waveforms shows that this component has an onset and offset which matches the duration of electrical stimulation. This component represents the CI DC artefact. Time waveforms are shown at the scalp location where amplitude was largest - Cz is located at the vertex and C5 is located laterally on the left side of Cz. Note the similar morphology of the artefact in the subthreshold and suprathreshold change condition. Mean scalp voltage maps between 50 and 120 ms after stimulus onset show that the distribution of CI artefact is biased towards the side of the implant.

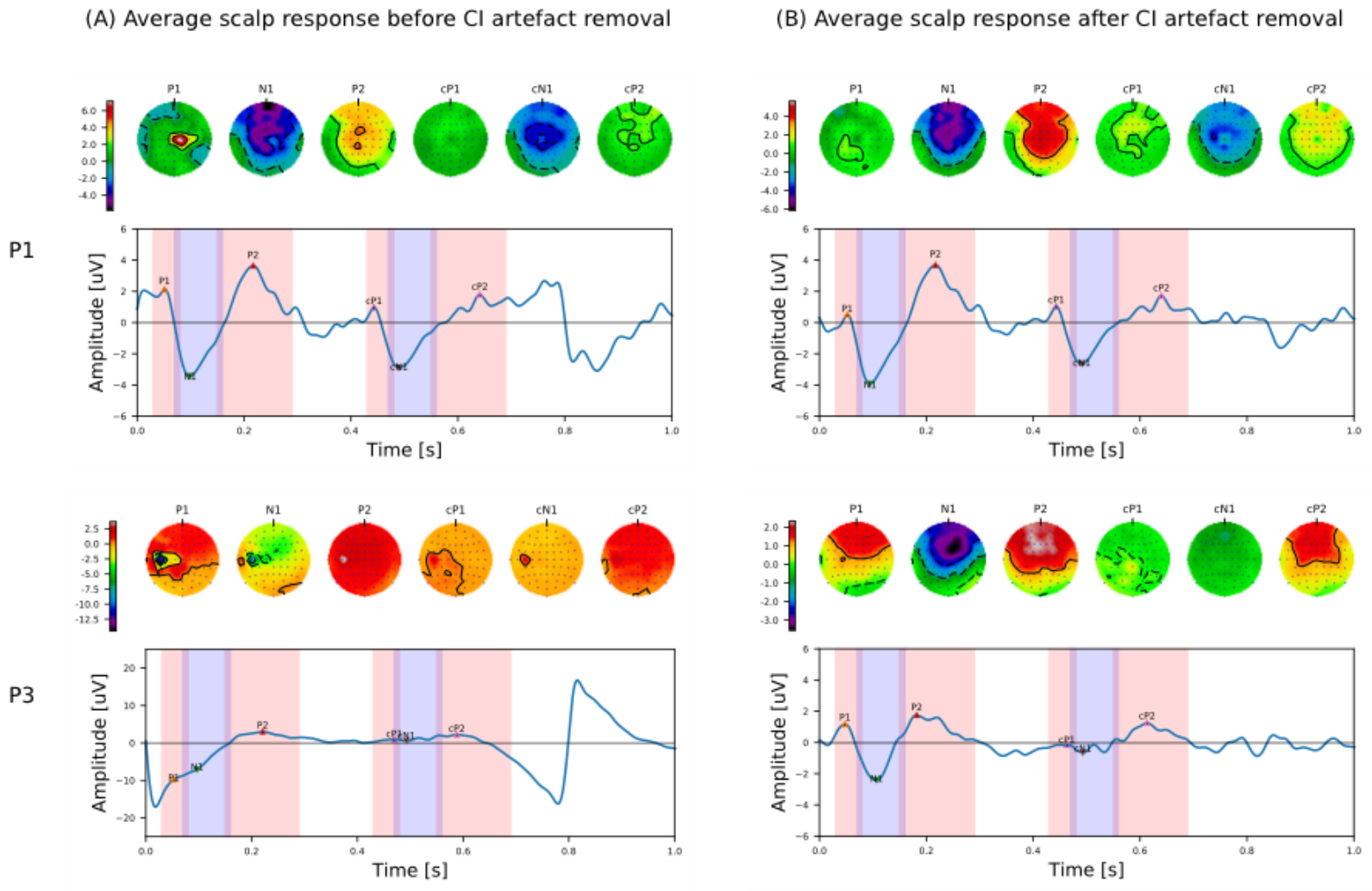

Figure 3. Cortical responses in participants P1 and P3 during the suprathreshold change condition. (A) Average scalp response referenced to the contralateral mastoid, before CI artefact removal. Onset and offset artefacts can be seen in both cases and a cortical response cannot be identified

in participant P3. Scalp voltage maps at peak time points also show evidence of CI artefact. (B) Average scalp response referenced to the contralateral mastoid, after CI artefact removal. Clear onset and ACC responses are seen in both participants now and scalp voltage maps at the different peak time points appear normal. The time windows used to detect positive and negative peaks for the onset response (P1, N1, and P2) and ACC (cP1, cN1, and cP2) are shown in pink and blue, respectively. The horizontal lines correspond to the level of residual noise. Isopotential contour lines are shown on scalp voltage maps with black lines.

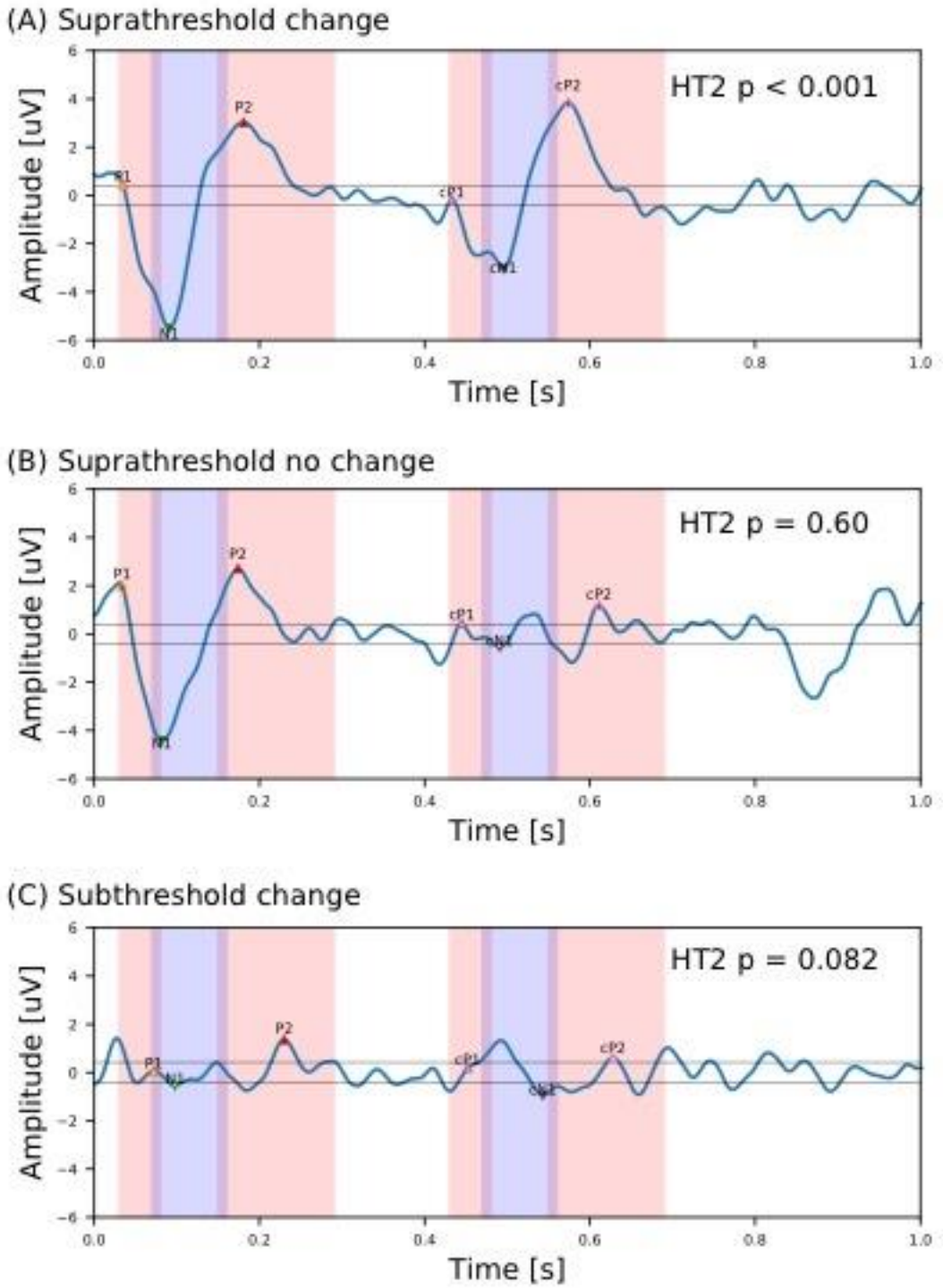

Figure 4. Cortical responses at channel FCz in participant P4. The ACC is seen in the suprathreshold change condition (A) but not the no change condition (B) or subthreshold change condition (C). Hotelling-T2 (HT2) p values are shown on each panel. The time windows used to detect positive and negative peaks are shown in pink and blue, respectively. The horizontal lines correspond to the level of residual noise.

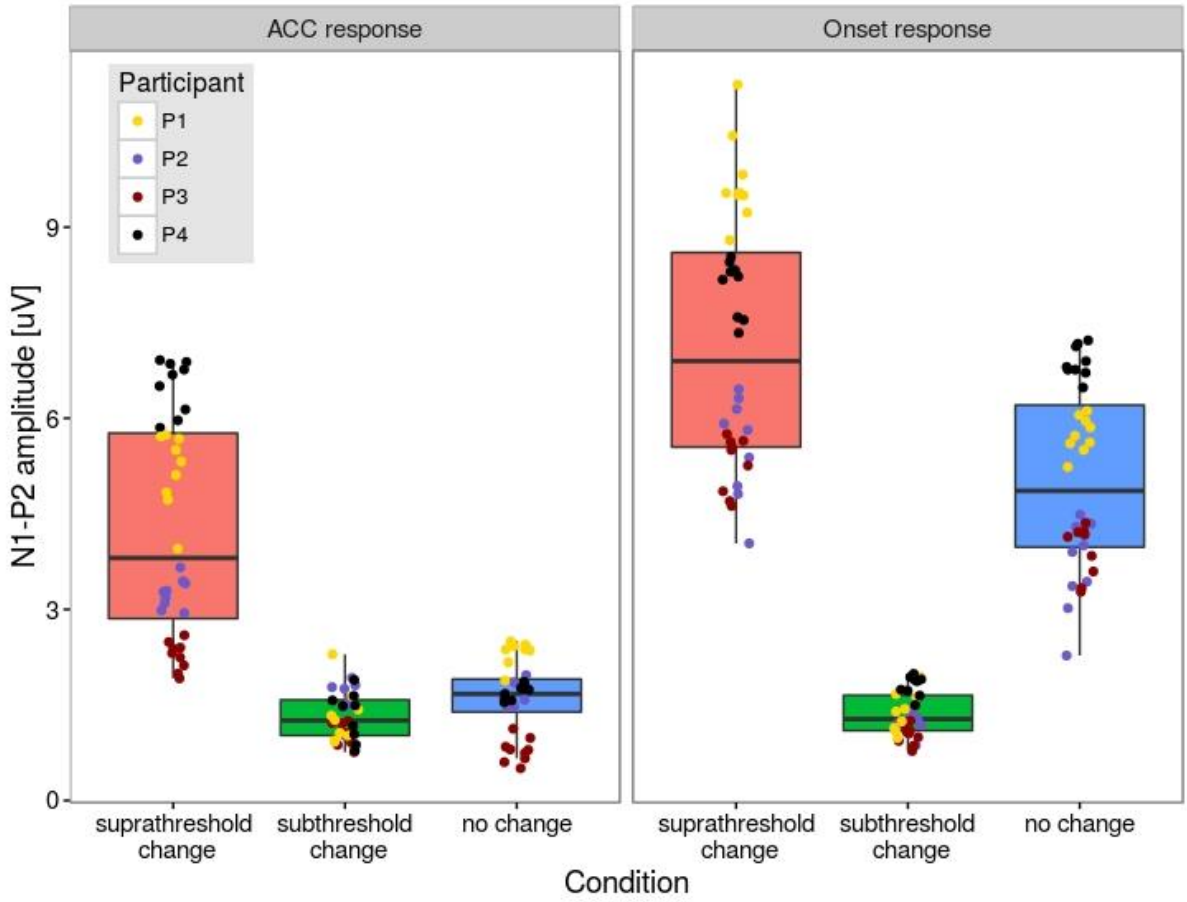

Figure 5. Boxplot of N1-P2 amplitude of the onset and ACC response for the three different stimulation conditions. Each point represents a different scalp location (Cz, C1, C2, FCz, FC1, FC2, Fz, F1, and F2) and a different colour is used for each participant. The upper and lower hinges of the box plots correspond to the first and third quartiles, whilst the median is indicated by the horizontal line within each box.

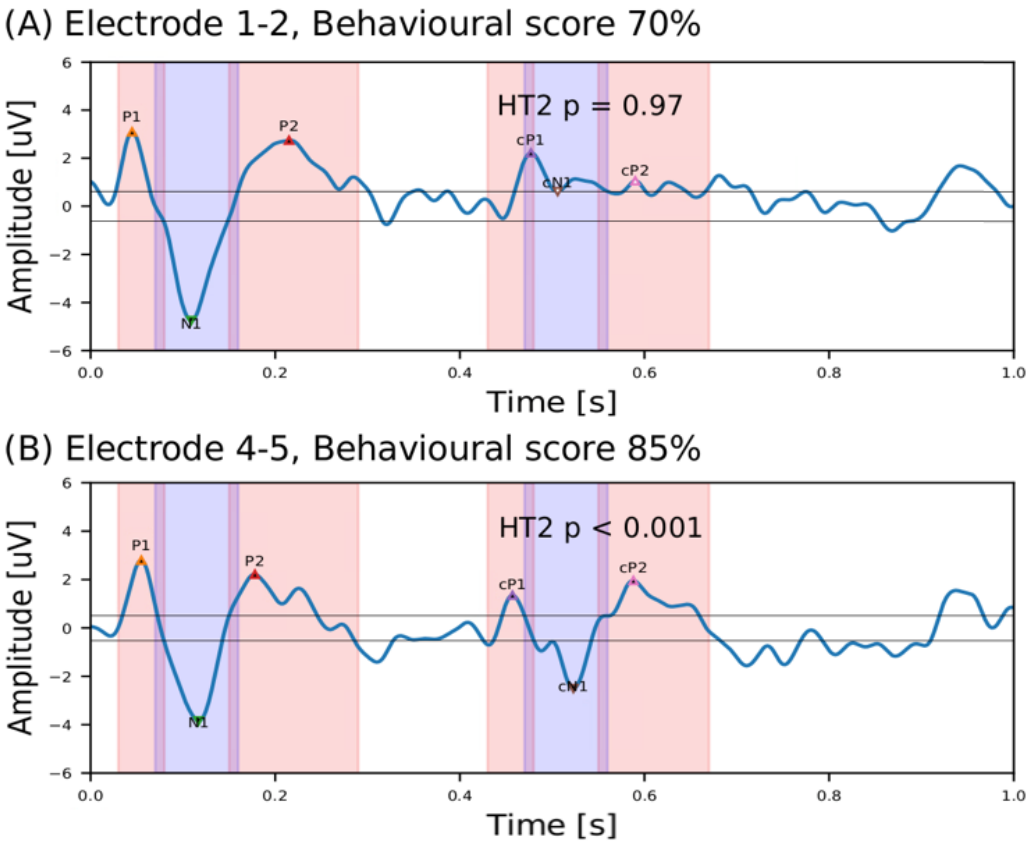

Figure 6. Cortical responses at FCz for two different electrode pairs in participant S1 showing agreement between the ACC and behavioural measurements. A behavioural fail is associated with an absent ACC (A) whilst a behavioural pass is associated with a clear ACC (B). The electrode pairs, behavioural scores and Hotelling-T2 (HT2) p value are indicated on each panel. The time windows used to detect positive and negative peaks are shown in pink and blue, respectively. The horizontal lines correspond to the level of residual noise.

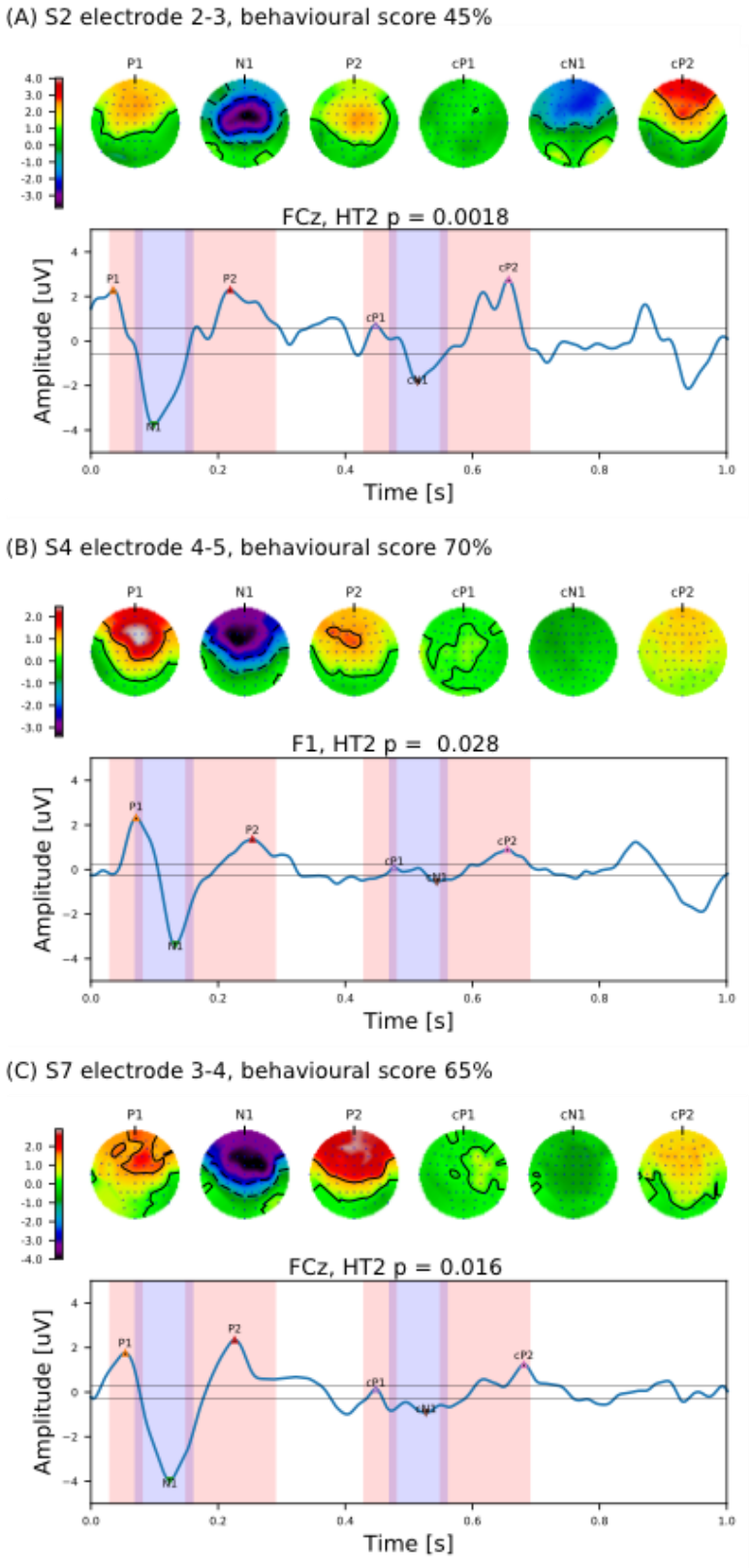

Figure 7. Cortical responses from electrode pairs that failed on behavioural testing but passed according to objective ACC criteria in three adults with pre-lingual onset deafness (S2, S4,

S7). Data are presented at a representative scalp channel which is shown on each panel with the corresponding Hotelling-T2 (HT2) p value. Scalp voltage maps at peak time points are shown above evoked response potentials, and show a similar pattern for the onset and ACC responses. The participant ID, electrode pair and behavioural discrimination score are shown above each panel. The time windows used to detect positive and negative peaks are shown in pink and blue, respectively. The horizontal lines correspond to the level of residual noise. Isopotential contour lines are shown on scalp voltage maps with black lines.

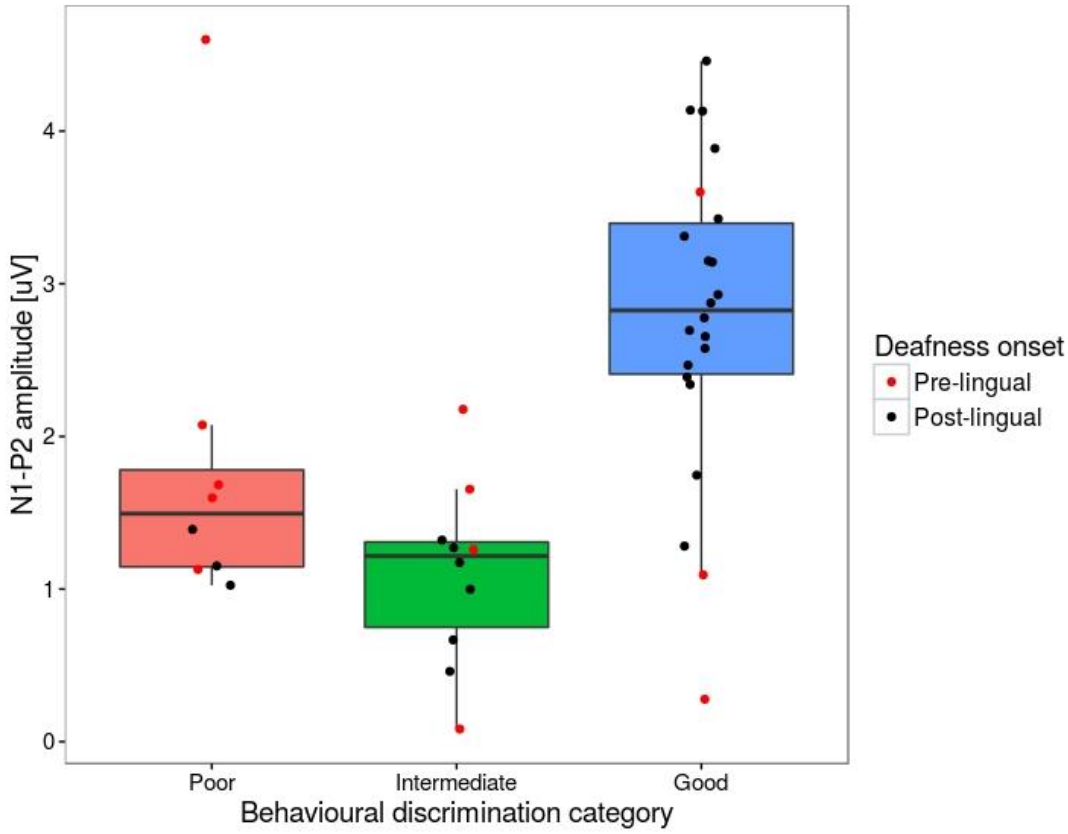

Figure 8. Relationship between ACC N1-P2 amplitudes and behavioural discrimination category. Depending on behavioural discrimination score, electrode pairs were categorized as being 'good' (score ≥ 80%), 'intermediate' (60-79%) or 'poor' (<60%). Data are shown for channel FCz. Each point represents an individual electrode pair. Red and black points are from adults with pre-lingual and post-lingual onset deafness respectively.
The upper and lower hinges of the box plots correspond to the first and third quartiles, whilst the median is indicated by the horizontal line within each box.

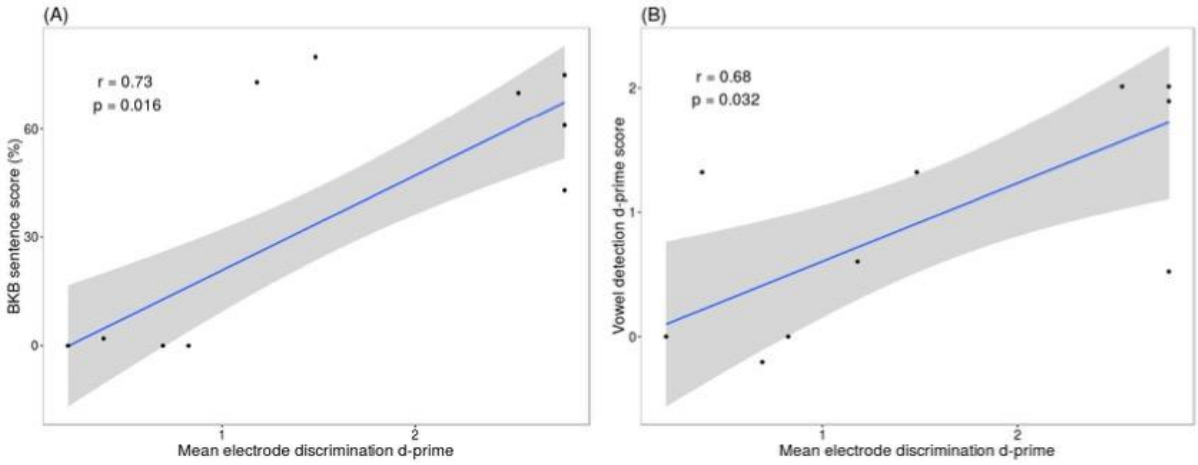

Figure 9. The relationship between (A) mean apical electrode discrimination d-prime score and open-set sentence perception measured with BKB sentences and (B) mean apical electrode discrimination d-prime score and closed-set vowel perception measured with CAPT. Each point represents data from a single participant. Standard error of the fitted line is shown by the shaded area.

Tables

Participant	Age	Sex	Ear	Risk factor for hearing loss	Communication	Duration profound hearing loss (years)	Duration implant use (years)	Electrode pair tested	Device	Electrode	Processing strategy
P1	41	F	R	Unknown	oral	39.5	6	9 and 7	AB HR 90K	Hifocus 1J	Hires Optima-S
P2	18	M	R	X linked inheritance	oral + sign	10	2	6 and 8	MED-EL CONCERTO	Flex 28	FS4
P3	66	M	L	Unknown	oral	16	9	9 and 11	AB HR 90K	Hifocus 1J	Hires P+ Fidelity 120
P4	68	M	L	Guillian Barre Syndrome	oral	5	5	6 and 10	MED-EL SONATA	Flex 28	HDCIS

Table 1. demographic details of participants in experiment 1. F= female, M= male, R = right, L= left, AB HR 90K = Advanced bionics HiRes 90K, FS4 = Fine structure 4, HDCIS = High definition continuous interleaved sampling

Participant	Age	Sex	Ear	Risk factor for hearing loss	Communication	Duration profound hearing loss (years)	4F-PTA non CI ear (dB HL)	Device	Electrode	Processing strategy
S1	51	M	R	Unknown	oral	10	116	HR 90K	Mid Scala	HiRes Optima-S
S2	50	F	R	Unknown	oral + sign	50	115	HR 90K	Mid Scala	HiRes Optima-S
S3	42	F	L	Unknown	oral	18	118	HR 90K	Mid Scala	HiRes Optima-S
S4	48	M	L	Maternal rubella	oral	46	115	HR 90K	1J	HiRes Optima-S
S5	47	F	L	Unknown	oral	42	103	HR 90K	Mid Scala	HiRes Optima-S
S6	68	F	L	Unknown	oral	10	100	HR 90K	Mid Scala	HiRes Optima-S
S7	57	F	L	Unknown	oral + sign	57	120	HR 90K	Mid Scala	HiRes-S
S8	51	F	R	Unknown	oral	5	96	HR 90K	Mid Scala	HiRes Optima-S
S9	48	M	L	Unknown	oral	1	113	HR 90K	Mid Scala	HiRes Optima-S
S10	80	M	L	Unknown	oral	10	78	HR 90K	Mid Scala	HiRes Optima-S

Table 2. demographic details of participants in experiment 2. F= female, M= male, R = right, L= left, 4F-PTA = four frequency pure tone average, CI = cochlear implant, HR 90K = HiRes 90K

Participant	ACC Discrimination Score	Behavioural Discrimination Score	Sentence score (BKB) (%)	Vowel score (CAPT) (%)
S1	2	2	80	65
S2	2	1	0	25
S3	4	4	61	40
S4	1	2	73	42.5
S5	0	0	2	65
S6	1	1	0	20
S7	1	0	0	25
S8	4	4	43	80
S9	4	4	70	82.5
S10	4	4	75	82.5

Table 3. The number of discriminable electrode pairs as determined with objective ACC and behavioural criteria as well as speech perception scores for BKB and CAPT tests for each participant.

	Peak latency measurements (ms)		
Waveform component	Mean	Standard deviation	Range
Onset P1	43	8	32-59
ACC P1	58	11	38-78
Onset N1	101	8	86-121
ACC N1	118	15	97-143
Onset P2	200	27	159-257
ACC P2	232	36	179-288
	Peak to peak N1-P2 amplitude (uV)		
Onset response	6.71	1.76	3.27-9.56
ACC	2.96	0.92	1.26-4.60

Table 4. Mean, standard deviation and range for peak latencies and peak-to-peak amplitudes at channel FCz. The first column shows the response type (onset or ACC) and peak label (P1, N1 and P2).

Participant	Electrode pair	Behavioural discrimination score (%)	N1-P2 peak amplitude (uV)
S1	1_2	70	0.66
	2_3	75	1.00
	3_4	100	2.34
	4_5	85	4.46
S9	1_2	100	2.87
	2_3	100	3.14
	3_4	90	2.70
	4_5	100	1.75

Table 5. ACC amplitude at channel FCz in 2 post-lingually deaf participants. This shows that even in the ‘good category’ (discrimination score ≥ 80%) a higher discrimination score is not necessarily associated with a higher ACC amplitude.