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Title

Development of electrophysiological and behavioural measures of electrode discrimination in adult cochlear implant users

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Abstract

The plasticity of the auditory system enables it to adjust to electrical stimulation from cochlear implants (CI). Whilst speech perception may develop for many years after implant activation, very little is known about the changes in auditory processing that underpin these improvements. Such an understanding could help guide interventions that improve hearing performance. In this longitudinal study, we examine how electrode discrimination ability changes over time in newly implanted adult CI users. Electrode discrimination was measured with a behavioural task as well as the spatial auditory change complex (ACC), which is a cortical response to a change in place of stimulation. We show that there was significant improvement in electrode discrimination ability over time, though in certain individuals the process of accommodation was slower and more limited. We found a strong relationship between objective and behavioural measures of electrode discrimination using pass-fail rules. In several cases, the development of the spatial ACC preceded accurate behavioural discrimination. These data provide evidence for plasticity of auditory processing in adult CI users. Behavioural electrode discrimination score but not spatial ACC amplitude was found to be a significant predictor of speech perception. We suggest that it would be beneficial to measure electrode discrimination in CI users and that interventions that exploit the plastic capacity of the auditory system to improve basic auditory processing, could be used to optimize performance in CI users.

Keywords

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

Abbreviations

AB, Advanced Bionics; ACC, auditory change complex; BKB, Bamford-Kowal-Bench; CAPT, CHEAR auditory perception test; CI, cochlear implant; EDL, electrode discrimination limen; Hotelling-T2, Hotelling’s t-squared; LME, linear mixed effects; MMN, mismatch negativity; NH, normal hearing; SMRT, spectral-temporally modulated ripple test

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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 not listed. RM, JU, PB and DV designed the experiment. DV and JU supervised the project. RM and JU collected and analyzed the data. RM, AS, DKS and DJ recruited participants. RM wrote the manuscript and all the other authors were involved in revising the manuscript.

1. INTRODUCTION

Cochlear implants (CIs) are auditory prostheses that bypass the damaged cochlea and provide direct electrical stimulation to auditory neurons. Electrical hearing imposes several limitations compared to acoustic hearing including reduced dynamic range, spectral mismatch between the characteristic frequencies of the auditory neurons and allocated frequencies of the stimulation channels, as well as reduced spectral resolution (Moore, 2003). Learning to hear and communicate effectively with a CI requires significant adjustment on the part of the auditory system. To be able to fully understand speech with a CI the individual needs to develop perceptual skills from detection and discrimination through to identification and comprehension (Erber, 1982). Whilst it is well known that a CI user's ability to identify speech can improve over long periods with hearing experience (Tyler et al., 1997), the time course for the emergence of discrimination ability is less well understood.

Understanding the temporal dynamics of discrimination ability could provide insights into the development of basic auditory processing and help guide management of CI users. In this respect, assessment of electrode discrimination is of particular interest. Although electrode discrimination is a multimodal percept (Collins et al., 1997), it is thought to be predominantly a measure of spatial resolution. Electrode discrimination ability has been correlated with speech perception in adult and paediatric CI populations (Busby et al., 2000; Dawson et al., 2000; Mathew et al., 2017) and the results of electrode discrimination tests have been used to optimize the CI map in a number of studies (Saleh et al., 2013; Vickers et al., 2016; Zwolan et al., 1997). However, if such interventions are to be carried out, then it would be helpful to understand how these psychophysical abilities develop over time. If performance improves for long periods with CI experience, then prematurely remapping the CI by deactivating electrodes or altering stimulation parameters could be detrimental. If on the other hand, performance improves rapidly and then plateaus, remapping interventions are more likely to be appropriate.

Relatively few studies have assessed the emergence of spectral processing in CI users. Sandmann et al. (2015) conducted a longitudinal study in newly implanted post-lingually deaf adult CI users who were given a behavioural task in which they had to identify the direction of pitch change in a frequency modulated tone complex. Participants were followed up for 9 months after switch-on but performance did not increase significantly after 2 months.

This study suggests that spectral processing, as measured with a task involving pitch judgements, plateaus very quickly. Landsberger et al. (2018) measured spectral resolution with the SMRT in a cross sectional study of paediatric CI users between the ages of 5 and 13 years. Most children had been using a CI for several years (range 0.8 – 11 years). It was found that SMRT scores were not correlated with age or CI experience suggesting that the development of spectral resolution is impaired in early deafened CI users. To date, no study has assessed the development of electrode discrimination in CI users.

Electrode discrimination can be measured with simple behavioural tasks and also with auditory evoked cortical responses. The advantage of electrophysiological measurements is that they allow objective assessment independent of attention, cognition and linguistic ability, which is particularly important in young children. Electrode discrimination can be measured objectively with two types of auditory evoked cortical responses. The first is the mismatch negativity response (MMN) - this is recorded with an odd-ball paradigm consisting of frequent standard stimuli and rare deviant stimuli. The second is the spatial auditory change complex (ACC) – this is a cortical potential in response to a change in stimulating electrode during a continuous stimulus. Whilst both the spatial ACC and the MMN have been used to measure electrode discrimination (Brown et al., 2008; He et al., 2014; Wable et al., 2000), there is evidence to suggest that the ACC is a more sensitive marker of peripheral discrimination (Martin and Boothroyd, 1999).

We recently showed that it is feasible to measure the spatial ACC in different types of CI devices and as early as 1-week after switch-on in adult CI users (Mathew et al., 2017). In addition, there was a strong relationship between objective and behavioural measures of electrode discrimination. Interestingly, in some pre-lingually deafened late implanted individuals, the spatial ACC could be measured despite relatively poor behavioural discrimination. We hypothesized that in these cases, the presence of the ACC indicated the potential to develop accurate behavioural discrimination at a later stage. In this follow up study, we assess how the spatial ACC and behavioural measures of electrode discrimination develop in relation to each other over time in newly implanted adult CI users. In addition, we examine how these measures of electrode discrimination are related to speech perception.

2. METHODS

2.1 Participants

Eleven participants ranging in age from 42 to 80 years took part in the study. Participants underwent behavioural and electrophysiological testing at the following time points after switch-on: 1 week (median 10.5 days, range 7-19 days), 3 months (median 92 days, range 81-108 days) and 6 months (median 180.5 days, range 169-190 days). Additionally, a subset of participants underwent behavioural testing at 12 months after switch-on (see section 2.5). One participant dropped out of the study after the first recording session and was therefore excluded from the analysis. Of the remaining 10 participants, 9 had taken part in our previous study (Mathew et al. 2017). All participants were unilaterally implanted with an Advanced Bionics (AB) Hi-Res 90K device with full electrode array insertion and normal electrode impedances. Demographic details of participants are shown in table 1. Of note, deafness onset was pre or peri-lingual in 3 cases and post lingual in the remainder.

Participants were recruited from University College London Hospital 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. All participants provided written informed consent prior to testing and received a small payment for taking part in the study.

2.2 Stimuli for measuring electrode discrimination

Stimuli were as described in our previous study (Mathew et al., 2017). The participants own speech processor was bypassed and electrodes were stimulated with a platinum sound processor through a research interface (BEDCS version 1.18.288 from AB). A schematic of the stimulus is shown in figure 1. The 4 most apical electrode pairs (1-2, 2-3, 3-4, 4-5), which typically encode frequencies of 250-828 Hz, were tested. Stimuli consisted of 800 ms alternating polarity biphasic pulse trains with a phase duration of 50 µs and pulse rate of 1000 pps. The first and last 12 ms of the stimulus consisted of zero amplitude pulses, during which the processor still communicates with the internal receiver. This period was included to reduce potential overlap between CI artefact and the cortical response. Alternating polarity stimuli were used, as averaging EEG responses due to opposite polarity stimuli reduces polarity dependent electrical artefacts (Hofmann and Wouters, 2010). The stimuli were presented at a rate of 0.51 Hz and a monopolar configuration was used. There was a change in stimulating electrode at the midpoint of the stimulus. The first electrode is referred to as the 'reference electrode' and the second electrode is referred to as the 'test electrode'. The cortical responses elicited by the reference and test electrodes are referred to as the 'onset response' and the 'ACC' respectively.

Stimuli were presented at the loudness balanced most comfortable (MC) level. The MC level for electrodes was determined by gradually increasing the stimulation level until participants indicated that loudness was at point 6 of a 10-point AB loudness chart. The average of two measurements was used as the final MC level. In order to reduce loudness cues when switching the active electrode, electrode pairs were carefully loudness balanced as described previously (Mathew et al. 2017). The stimulation level of the test electrode was initially set at the MC level of the reference electrode. The reference and test electrode were then stimulated in sequence separated by a gap of 600 ms. Based on feedback from the participant, the experimenter adjusted the level of the test electrode until both stimuli were perceived to have the same loudness. The average of the three measurements was used as the loudness balanced MC level. The order of loudness balancing was as follows: electrode 4 with electrode 3, electrode 5 with electrode 4, electrode 2 with electrode 3 and electrode 1 with electrode 2. As stimulation levels required by CI users generally increase over the first 6 months of CI use (Vargas et al., 2012), this procedure for determining stimulation levels was repeated at each visit until 6 months.

2.3 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. 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.

2.4 EEG processing

Recordings were processed off-line using a custom analysis module in Python 2.7. Unconnected or 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 (Gasser et al., 1992). CI artefact removal and noise reduction was performed using spatial filtering as described previously (Cheveigné and Simon, 2008; Mathew et al., 2017). Per-channel time averages were obtained by applying a weighted averaging method (Don and Elberling, 1994).

The presence or absence of the ACC was determined objectively by means of the Hotelling's t-squared (Hotelling-T2) test (Golding et al., 2009; Mathew et al., 2017). This tests whether activity in a 'response window' is significantly different from 0. The typical response window was between 450 – 650 ms after stimulus onset for the ACC response, as this window usually encompassed the P1, N1 and P2 peaks of the ACC. For 8 out of 120 recordings the response window was made longer due to a late P2 component and in 2 out of 120 recordings the response window was made shorter due to an absent P2 component. An objective ACC pass for an electrode pair was defined as a Hotelling-T2 with p value < 0.05 in > 4 out of 9 scalp channels at frontal and central sites, where the ACC is most prominent (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. Time windows for peak detection were adjusted where required following visual inspection of responses. Although the Hotelling-T2 was used to determine whether the ACC was present or absent, the magnitude of the response was quantified by measuring N1-P2 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.

2.5 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 with the test electrode occurring with equal probability in either the second or third interval. Participants were instructed to choose the interval that was different and feedback was not provided. Stimuli consisted of alternating polarity biphasic pulse trains from a single electrode, with pulse rate of 1000 pps, phase width of 50 μs, monopolar mode of stimulation 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% as per our previous study (Mathew et al., 2017). Behavioural scores were converted to d' scores with a maximum of 2.77 based on a correction factor for a score of 100% (Stanislaw and Todorov, 1999). Retesting was done at 12 months for individuals who did not have a behavioural pass for all electrode pairs by 6 months in order to determine if there are longer term changes in electrode discrimination ability. Loudness balancing was checked and repeated if participants reported a difference in loudness.

2.6 Speech perception testing

Speech perception testing was conducted using the AB-York Crescent of Sound (Kitterick et al., 2011) in a sound treated booth. The Crescent of Sound is a speaker array developed for clinical and research testing. A single speaker from the array was used in this study. A single speaker at a distance of 1m from the participants was used in this study. Open-set sentence and closed-set vowel were tested, with no feedback provided. 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 (Vickers et al., 2018). The CAPT is a four-alternative-forced-choice monosyllabic word-discrimination test spoken by a female British English speaker. Listeners were asked to respond by choosing from four pictures on a computer screen. Stimuli were presented at 60 dBA in quiet. This level was intended to be lower than comfortable in order to challenge the auditory system and understand how well an individual can understand speech in non-ideal conditions. The test was repeated to give a total score out of 40 trials. This was converted to a d' 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 1). However, it is unlikely that hearing from the contralateral ear affected this participant's speech scores as his unaided (i.e. no CI or hearing aid) BKB sentence score was 0%. EEG, behavioural and speech testing were done in a single session that lasted approximately 2.5 hours including breaks.

2.7 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. 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. RESULTS

3.1 Changes in behavioural electrode discrimination

Figure 2 shows the change over time in mean behavioural discrimination score across 4 electrode pairs for each participant. As stated in the methods, the 12-month data only contained new results for participants who had not achieved a behavioural pass for all 4 electrode pairs by 6 months (S1, S2, S5, S6).

Inspection of the individual data shows that there was large variability in discrimination scores as well as the pattern of change over time. Participants S3, S8, S9 and S10 had excellent performance from 1 week with scores at or near ceiling level for all electrode pairs. Participants S4 and S11 showed a rapid increase in behavioural scores achieving ceiling/near-ceiling level by 3 months. In contrast, participants S2, S5 and S6 had relatively poor discrimination to start with, but mean discrimination score increased over 12-months. Only participant S1 showed a decrease in mean behavioural score. This participant had excellent discrimination for electrode pairs 3-4 and 4-5 throughout the study and the decrease in mean score was due to random variation in performance for electrode pairs 1-2 and 2-3, for which the threshold for a behavioural pass was never achieved.

The change in behavioural discrimination score over time was analyzed with a linear mixed effects model. Only electrode pairs that did not have a discrimination score of 100% at 1 week were included in this analysis. The dependent variable was the 'behavioural d' score' for each electrode and the independent variables were 'time after switch-on' and 'electrode pair' (1-2, 2-3, 3-4, 4-5). There was no significant effect of 'electrode pair' and this factor was therefore removed from the model. Analysis of the reduced model showed a significant effect of 'time after switch-on' ($F(3,67) = 5.01$, $p < 0.001$). Post-hoc pairwise comparisons with Tukey correction showed there was a significant difference for the 1 week vs 12 month contrast ($p = 0.002$) and a trend towards significant difference for the 1 week vs 6 months contrast ($p = 0.054$).

Changes in behavioural electrode discrimination were also analyzed in terms of the number of electrodes with a behavioural pass. In this case, the maximum score for an individual at any time point is 4, corresponding to the number of electrode pairs tested. The changes over time in the number of electrodes with a behavioural pass are shown in figure 3. This figure shows a similar pattern to figure 2 with a marked improvement in electrode discrimination ability for participants S2, S5 and S6 between 6 and 12 months. The total number of electrodes with a behavioural pass increased over time and was 25/40 at 1 week, 29/40 at 3 months and 30/40 at 6 months. At 12 months, 5 additional electrode pairs achieved a behavioural pass.

These data show that apical electrode discrimination ability varies widely amongst CI users but can continue to improve for up to 12 months after switch-on in certain individuals.

3.2 Behavioural discrimination controlling for loudness intensity

Studies from normal hearing (NH) and CI populations have shown that discrimination ability improves with stimulation level (Freyman and Nelson, 1991; McKay et al., 1999). In this study, most participants reported higher MC levels over time and therefore higher stimulation levels were generally used for testing at later time points. The average MC level across participants was 250 μA at 1 week, 294 μA at 3 months and 313 μA at 6 months. Thus, the increase in stimulation levels could potentially account for the improvement in behavioural discrimination scores.

In order to investigate whether improvements in behavioural discrimination were due to the use of higher stimulation levels, electrode pairs were re-tested at later time point using stimulation levels from the first time point. If discrimination scores at the later time point were higher than that obtained with the same stimulation level as originally used, then this would provide evidence that improvements over time were not just due to the use of a higher stimulation level. Behavioural electrode discrimination was therefore re-tested for electrode pairs that developed a behavioural pass from a behavioural fail. This was performed at a median of 16 months after switch-on (range 12 – 20 months) using the 1-month and/or 3-month stimulation levels. For example, if an electrode pair developed a behavioural pass at 12 months, then it was re-tested at the 1-week level. If a behavioural pass was achieved (score ≥ 80%), then no further testing was performed but if there was a behavioural fail, re-testing was repeated using the 3-month level. The 6-month level was not used for re-testing as this was the same level used at 12 months. Re-testing of electrode discrimination at earlier levels was done in a separate session to the main experiment in order to reduce within session learning effects. In addition, loudness balancing was checked and repeated if necessary, for all electrode pairs and stimulation levels.

The results of re-testing are shown in table 2. There were 10 electrodes from 5 participants that developed a behavioural pass from a behavioural fail with implant listening experience. When re-tested at the original 1-week level, 9 out of 10 electrode pairs had a higher score, with 7 of these achieving a behavioural pass (score ≥ 80%). Of the 3 electrode pairs that had not achieved a behavioural pass at the 1-week level, 2 achieved a behavioural pass when re-tested at the 3-month level. As can be seen from table 2, improvements occurred irrespective of whether electrodes were loudness balanced again or not. Only one electrode failed when re-tested at the 1-week and 3-month levels (S6, electrode 3-4). This electrode had a behavioural fail at 6 months (score = 60%) but when tested at 12 months, with the same stimulus level, a behavioural pass was achieved (score = 85%). Therefore, all ten electrode pairs that originally had a behavioural fail, developed a behavioural pass when re-tested with the same stimulus level at a later time point.

The effect of time on behavioural discrimination score, with stimulation levels fixed was analyzed with a linear mixed effects model. The dependent variable was the behavioural discrimination d' score and independent variables included 'electrode pair' (1-2, 2-3, 3-4, 4-5), 'level' (1-week or 3-month level) and 'time' (original or re-test). This analysis showed that there was only a significant main effect of time ($F(1,20) = 32$, $p < 0.001$). These data demonstrate that electrode discrimination ability can improve with CI experience irrespective of stimulation level.

3.3 Development of the spatial ACC

Figure 4 shows the change over time in mean spatial ACC amplitude across 4 electrode pairs for each participant. The solid black line represents the grand mean across participants and was 2.16 μV at 1 week, 2.65 μV at 3 months and 2.79 μV at 6 months. Inspection of the individual data reveals large inter-individual variability in spatial ACC amplitude and the changes over time appear to be less consistent in comparison to the behavioural discrimination scores. However, a clear increase in spatial ACC amplitude with time can be observed in 7 out of 10 participants.

The change in spatial ACC amplitude was analyzed with a linear mixed effect model. The dependent variable was the spatial ACC amplitude for individual electrode pairs and the fixed effects were time after switch-on (1 week, 3 months and 6 months) and electrode pair (1-2, 2-3, 3-4, 4-5). There was no significant effect of electrode pair and this factor was therefore removed from the model. Analysis of the reduced model revealed a significant effect of time after switch-on ($F(2,108) = 4.93$, $p = 0.0089$). Post-hoc analysis with Tukey correction showed that there was a significant difference in ACC amplitude for the 1 week vs 6 months contrast ($p = 0.01$) and a trend towards significant difference for the 1 week vs 3 months contrast ($p=0.056$).

Analysis of the ACC with pass-fail criteria also showed that electrode discrimination ability improved with time. According to Hotelling-T2 criteria, the number of electrodes with an objective pass was 23/40 at 1 week, 28/40 at 3 months and 30/40 at 6 months. Figure 5 shows an example from participant S4, where the spatial ACC was absent at 1 week but developed into a clear response by 3 months.

The change in latency of the ACC was only assessed for electrode pairs for which there was an objective pass, as a meaningful latency cannot be obtained when the ACC is absent. This analysis was limited because a large proportion of the data had to be excluded. The mean latency at 1 week, 3 months and 6 months was 119ms, 123ms and 120ms for the ACC N1 peak and 224ms, 245ms, and 237ms for the ACC P2 peak. A mixed model analysis did not show any significant change over time in ACC peak latencies.

3.4 Relationship between objective and behavioural measures

The relationship between objective ACC and behavioural measures of electrode discrimination using pass-fail rules is shown in table 3. As described in the methods section, an objective ACC pass was based on Hotelling T2 statistical criteria whilst a behavioural pass required a discrimination score of at least 80%. Out of 120 measurements over 6 months, there was agreement between objective and behavioural measures in 99 cases: 34/40 at 1 week, 35/40 at 3 months and 30/40 at 6 months. There were 12 electrode pairs from 4 participants in which there was a behavioural pass but an objective fail. Of these disagreements, 8 were from participant S11 (disagreements: 2 at 1 week, 2 at 3 months and 4 at 6 months). Aside from this participant, there were only 4 electrode pairs from 3 participants in which there was a behavioural pass but an objective fail.

Interestingly, there were 9 cases where disagreement was due to an objective ACC pass despite a behavioural fail. Figure 6 shows examples of ACC recordings that fell into this group. Table 4 shows that the disagreements arose from 7 electrode pairs from 4 participants, 3 of whom had pre or peri-lingual onset deafness. In 6 out of these 7 cases, electrode pairs developed accurate behavioural discrimination at a later time point i.e. the ACC preceded accurate behavioural discrimination. As seen in table 4, in most cases a behavioural pass was obtained at the test point immediately following the attainment of an objective pass. However, for electrode pair 2-3 in participant S2, a behavioural pass was only obtained at 12 months despite an objective pass being present from 1 week onwards. The ability of the ACC to predict development of behavioural discrimination can be assessed by comparing the proportion of electrodes with an objective pass and objective fail that develop a behavioural pass at a later time point. Thus, while 6/7 electrode pairs (86%) with an ‘objective pass-behavioural fail’ developed a behavioural pass at a later time point, only 4/9 electrode pairs (44%) with an ‘objective fail-behavioural fail’ developed a behavioural pass. These data confirm our previous findings that a stimulus change may be encoded in the auditory pathway despite poor behavioural discrimination. Furthermore, the longitudinal data suggest that the presence of the ACC indicates potential to develop accurate behavioural discrimination at a later stage.

The relationship between objective and behavioural measures of electrode discrimination was also assessed by performing correlation analysis across participants between mean behavioural d’ score and mean ACC N1-P2 amplitude at each time point. Pearson’s correlation did not show a significant relationship at any time point (1 week: $r = 0.59$, $p = 0.072$, 3 months: $r = 0.55$, $p = 0.098$, 6 months: $r = 0.13$, $p = 0.71$; $N = 10$ for all correlations). The correlation was particularly poor at 6 months, which was also reflected in the greater level of disagreement in the pass-fail analysis at this time point as seen earlier. The correlation results however, must be interpreted with caution as the study was underpowered for this analysis.

3.5 Relationship between speech perception and electrode discrimination

Figure 7 shows how sentence and vowel perception scores changed over time. The solid black line represents the mean speech perception score across all participants. Vowel perception and open-set sentence perception improved over time in all participants except S2, in whom the sentence perception score remained at 0% throughout. This participant was congenitally deafened and used both oral and sign language.

It is interesting to note that participants S2, S5 and S6, who had relatively poor electrode discrimination at 6 months (see figure 2), were also three of the poorest performers in terms of speech perception at 6 months. On the other hand, participant S1 could only discriminate 2 out of 4 electrodes accurately throughout the 12-month study period but had consistently excellent speech perception scores. Participant S8 showed the opposite pattern, with excellent electrode discrimination but relatively poor speech perception.

The factors affecting speech perception were investigated with a linear mixed effects model where the dependent variable was ‘speech perception score’ (either sentence perception or vowel perception score) and the independent variables were ‘time after switch-on’ (1 week, 3 months, 6 months), ‘deafness onset’ (pre-lingual or post-lingual) and ‘mean behavioural electrode discrimination d’ score’ (averaged across 4 electrodes for each participant). For both vowel and sentence perception, there was no significant effect of deafness onset and this factor was therefore removed from the model. For sentence perception as the dependent variable, there was a significant main effect of ‘time after switch-on’ (F(2,18) = 4.80, p = 0.022) and ‘mean behavioural electrode discrimination d’ score’ (F(1,18) = 6.22, p = 0.021). Similarly for vowel perception score as the dependent variable, there was a significant main effect of ‘time after switch-on’ F(2,19) = 6.84, p = 0.0059) and ‘mean behavioural electrode discrimination d’ score’ (F(1,14) = 5.73, p = 0.032).

In order to investigate whether there is a relationship between the spatial ACC and speech perception, the mixed model analysis was repeated with speech perception score (either sentence perception or vowel perception score) as the dependent variable and ‘mean spatial ACC amplitude’ (averaged across 4 electrode pairs), ‘deafness onset’ (pre-lingual or post-lingual) and ‘time after switch-on’ on’ (1 week, 3 months, 6 months) as the independent variables. The analysis confirmed a significant main effect of ‘time after switch-on’ for sentence perception (F(2,18) = 9.38, p = 0.001) and for vowel perception (F(2,18) = 9.79, p = 0.001). However, there was no significant effect of ‘mean spatial ACC amplitude’ or ‘deafness onset’ in either case. The analysis was repeated with the fixed factor ‘number of objective discriminable electrode’ (ranging from 0 to 4) instead of the ‘mean spatial ACC amplitude’ but a significant effect for this factor was still not observed.

These data show that both sentence and vowel perception improve with hearing experience in CI users. Although behavioural and objective measures of electrode discrimination are related, the former appears to be the more important predictor of speech perception.

4. DISCUSSION

In this study, we have shown that electrode discrimination ability can improve markedly with CI experience and that this improvement can occur over relatively long periods of time. Changes in behavioural performance were paralleled by an increase in the amplitude of the spatial ACC, providing evidence for plasticity of auditory processing in adult CI users.

Furthermore, we have shown that behavioural electrode discrimination is a significant predictor of speech perception. Targeting improvements in spatial resolution could therefore lead to better hearing outcomes in CI users.

4.1 Changes in electrode discrimination over time

To the best of our knowledge, this is the first study to examine changes in electrode discrimination ability over time in CI users. Electrode discrimination ability continued to improve for up to 12 months after switch-on in certain individuals. While it is known that speech perception in CI users may improve for many years (Heywood et al., 2016; Tyler et al., 1997), it was somewhat surprising that discrimination of, what are in principle, simple stimuli would continue to improve for so long. The relatively long time course of improvement in some individuals suggests that central rather than peripheral factors, are responsible for the change in performance over time. The late improvements occurred in poorer performers, 3 of whom had pre or peri-lingual onset deafness, indicating that the history of hearing loss may account for the different time course of change in different individuals.

The data suggest that the improvements over time were not just due to task related learning for two reasons. Firstly, the improvements in behavioural scores over the first 6 months were paralleled by an increase in the mean spatial ACC amplitude. Secondly, all but one participant could accurately discriminate at least one electrode pair from the first test session. This implies that participants were competent at the behavioural task from an early stage and improvements in discrimination ability over time were more likely due to perceptual rather than task related learning. For example, participants S2 and S6 achieved a behavioural pass for only a single electrode pair from 1 week to 6 months but then showed improved discrimination for other electrode pairs at 12 months.

There is limited evidence from longitudinal studies that spectral resolution improves with CI experience. Sandmann et al. (2015) showed that in post-lingually deaf CI users, the ability to judge the direction of pitch change in a modulated tone complex increased rapidly until 8 weeks after switch-on and thereafter plateaued. The individual behavioural data was not presented in that study but the rapid asymptotic performance is similar to that seen in the good performers in our study who achieved electrode discrimination ceiling levels by 1 week to 3 months. Jeon et al. (2015) provide evidence of more long term improvements in spectral resolution using spectral ripple discrimination tests. In their study, spectral ripple discrimination scores of 4 post-lingually deafened adults were reported at a mean of 2 years and 12 years of CI use. In 3 out of 4 participants, scores increased over time, with considerable improvement in 2 cases. In contrast, Landsberger et al. (2018) found that spectral resolution as measured with the SMRT did not improve with age in paediatric CI users. However, this was a cross-sectional study and most CI users had been using their device for several years so it is possible that the spectral resolution had improved prior to testing. The different findings in these studies are likely due to differences in the behavioural task and study populations. However, taken together, it appears that improvements in spectral/spatial resolution predominantly occur during the first few weeks to months after switch-on but further gains may be possible over long periods of time in certain individuals.

In our study, improvements in behavioural electrode discrimination were accompanied by an increase in spatial ACC amplitude over the first 6 months of CI use. Whilst changes in the spatial ACC over time have not been previously reported, a number of studies have assessed longitudinal changes in discrimination ability in CI users using MMN measurements (Lonka et al., 2013, 2004; Purdy and Kelly, 2016; Vavatzanidis et al., 2015). In general, these studies have shown an increase in MMN amplitude with CI experience but in most cases the MMN could not be recorded in the early period after switch-on. As most studies do not report concurrent behavioural data, it is not clear whether the early absence of the MMN is due to the inability of CI users to discriminate the relevant stimuli or due to a lack of sensitivity in the recording paradigm.

Purdy et al. (2016) measured the MMN to a change in frequency using pure tone stimuli and showed that MMN amplitude increased and latency decreased during the first 9 months of CI use, though this effect was not statistically significant. Of note, the MMN could not be recorded in the first week after switch-on in 40% of cases, despite the stimuli being behaviourally discriminable suggesting a lack of recording sensitivity. Similarly, Lonka et al. (2004) and (2013) measured the MMN to vowel contrasts and a change in pure tone frequency respectively. In both studies, the MMN could not be recorded until 1 year after switch-on due to large CI artefact. Nonetheless, there was a significant increase in MMN amplitude from 1 year to 2.5 years after switch-on. Behavioural discrimination data were not reported in their study, although concurrent improvements in speech perception occurred over the same period. Pantev (2005) reported long term changes in acoustic ACC responses, using a continuous pure tone stimulus with a regular 100 Hz change in frequency, in 2 post-lingually deafened adults. The ACC could not be recorded for the first 2-3 months after switch-on in either case. Thereafter, the response increased in amplitude until 6 months for one user and for 2 years in the other user. These electrophysiological data provide evidence of long-term plasticity for auditory discrimination in CI users, though the time course for development appears to vary depending on subject factors and the type of stimuli.

We did not find an effect of CI experience on the latency of the N1 or P2 components of the spatial ACC response. It must be noted that the study was underpowered for this analysis as only measurements with an objective ACC pass could be included in order to obtain a meaningful latency value. Purdy et al. (2016) examined changes in MMN latency for pure tone stimuli in 10 adults with CI who were followed up on 5 occasions over 9 months after switch-on. It was found that there was a decrease in the MMN latency over time but this was not statistically significant. Lonka et al. 2013 did not find an effect of CI experience on the MMN latency. In contrast, a number of studies have reported that with CI experience there is a shortening of latency of the cortical response to sound onset (Burdo et al., 2006; Sandmann et al., 2015; Sharma et al., 2005). This difference may be because the ACC and MMN are markers of auditory discrimination rather than detection. In addition, He et al. (2012) showed that increasing the magnitude of change across different acoustic dimensions, such as frequency or intensity, led to consistent changes in the ACC amplitude but not the ACC latency, indicating that the latter is a poorer marker of discrimination.

An important confound to consider with behavioural and electrophysiological measurements over time is the stimulus level. During the first 6 months after CI, stimulation levels required by patients increase (Vargas et al., 2012) due to the development of loudness tolerance. It is known that for the cortical response to sound onset, increasing stimulus level leads to larger amplitude and shorter peak latency in both NH and CI populations (Firszt et al., 2002; Picton et al., 1976). This effect of stimulus level on evoked response has not been controlled for in the aforementioned MMN studies. In CI users, improved electrode discrimination scores with stimulus level have been reported, though there is much variability between individuals and even between electrode locations within an individual (McKay et al., 1999; Pfingst et al., 1999). When electrode pairs that originally had a behavioural fail were re-tested at a later time point with the original stimulation levels, significantly higher discrimination scores were obtained. This shows that improvements in behavioural discrimination over time cannot be completely accounted for by the increase in stimulation level. It is still possible that the changes in spatial ACC amplitude over time were due to level effects. Nonetheless, we consider it an important finding that the spatial ACC amplitude can increase at a relatively constant perceptual level and that this is paralleled by improvements in behavioural electrode discrimination.

4.2 Reasons for improved electrode discrimination

Reiss et al. (2007) showed that the pitch percept associated with an individual electrode can change by up to 2 octaves over time. This appears to be driven by the spectral mismatch between the allocated frequencies of the CI stimulation channels and the characteristic frequencies of the corresponding auditory neurons. Hence, the absolute percept associated with an electrode may change over time, but this does not imply better spatial resolution. It is therefore interesting to consider two questions.

Firstly, what was driving the improvement in spatial resolution in CI users given that they did not undergo any discrimination training? The improvements could be due to top-down processes - exposure to speech and the feedback that CI users obtain through their daily interactions, are in essence ‘passive training’, which could drive better spatial resolution. Such a top-down effect was seen in the study by Rosen et al. (1999) who showed that connected discourse tracking training resulted in improved vowel recognition in CI simulations with NH listeners. Improvements in spatial resolution could also occur due to passive exposure to electrical stimulation through the CI. Kurkela et al. (2016) passively exposed rats to behaviourally irrelevant speech stimuli for 36 hours. They showed that the MMN for small changes in spectrotemporal sounds could be recorded in animals previously exposed to these sounds but not in the animals exposed to different sounds. The authors suggest that passive exposure to sounds can result in a formation of long-term memory representation and this presumably aids auditory discrimination.

Secondly, how and where do improvements in spatial resolution occur in the auditory pathway? Animal studies have shown that chronic auditory stimulation with a CI leads to re-organization of cortical and sub-cortical structures (Kral and Tillein, 2006; Moore et al., 2002). Whilst tonotopic representation of sound is absent in the auditory cortex of neonatally deafened cats, there is evidence that chronic stimulation with a CI can lead to partial restoration of tonotopicity (Fallon et al., 2009). Dinse et al. (2003), however, found that a 3-month period of CI stimulation in neonatally deafened adult cats did not lead to normal patterns of auditory cortex activation. Rather, individual electrodes were associated with broad patterns of overlapping cortical activation and reduced cortical tonotopy compared to

NH cats. The authors suggest that perceptual improvements are not due to restoration of normal patterns of cortical activation, but rather are due to learning effects mediated by large populations of overlapping neurons. There is evidence that the area of cortical activation is related to behavioural discrimination performance. Recanzone et al. (1993) showed that frequency discrimination training in owl monkeys led to an increase in the area of representation in the auditory cortex, as well as sharper cortical tuning for the trained frequencies. Of note, the area of representation was correlated with behavioural discrimination performance suggesting that the cortical spatial code is important for frequency discrimination. Improved electrode discrimination in CI users, may be due to increased cortical representation of electrodes in association with higher auditory learning. There is, however, evidence for tonotopic organization in the auditory cortex of adult CI users (Guiraud et al., 2007). It is therefore possible that long-term use of a CI leads to restoration of tonotopy in the auditory pathway. At this point in time, the mechanism by which auditory discrimination improves in CI users remains poorly understood and further research into this area is required.

4.3 Electrode discrimination and speech perception

Similar to our previous study (Mathew et al., 2017), we found that behavioural electrode discrimination score is a significant predictor of speech perception. Apical electrodes encode low frequencies, which provide important cues for speech perception including manner of articulation information, some voicing cues, first formant and the associated transition cues between phonemes (Raphael et al., 2007). It follows that if discrimination in this region is poor, speech cues will be lost. Our results are in keeping with studies that have shown a negative correlation between apical electrode discrimination limens (EDL) and speech perception (Busby et al., 2000; Dawson et al., 2000; Henry et al., 2000). It must be borne in mind that only a limited range of electrodes were tested in this study and the allocated frequencies would only cover the first formant region in speech. Apical electrode discrimination does not necessarily reflect discrimination ability in the rest of the CI array. This may explain the disparity between electrode discrimination performance and speech perception in certain participants such as S8, who had excellent apical electrode discrimination but relatively poor sentence perception, or S1, who had relatively poor apical discrimination but excellent speech perception.

We did not find a relationship between the amplitude of the spatial ACC and speech perception. Similarly, Wable et al. (2000) measured electrode discrimination around a single apical electrode with the MMN and did not find a correlation between speech perception and MMN latency or amplitude. There could be a number of reasons for a lack of a relationship between the spatial ACC and speech perception across participants. Firstly, there is large inter-individual variability in the size of the ACC even in NH listeners (He et al., 2012). Secondly, the ACC response did not always reflect behavioural discrimination ability (discussed further in section 4.4). In a number of cases the spatial ACC could be recorded despite poor behavioural discrimination, and appeared to reflect discrimination potential rather than ability. It may be that the spatial ACC is a more strongly correlated with speech perception in experienced CI users in whom the the full potential for discrimination has been achieved. Indeed, He et al. (2014) found that the EDL measured around a mid-array electrode with the spatial ACC was associated with speech perception when categorized as ‘good’ or ‘poor’. Of note, most of the participants in their study had several years of CI experience.

In summary, these data provide further evidence that electrode discrimination is related to speech perception. Interventions that enhance spatial resolution may therefore improve hearing performance.

4.4 Relationship between the spatial ACC and behavioural electrode discrimination

We found a high level of agreement between the spatial ACC and behavioural discrimination. In 12 out of 120 cases however, the ACC could not be recorded despite accurate behavioural discrimination. Eight of these ‘false negative’ recordings were from participant S11. The absence of a response was thought to be due to overlap between a prolonged onset response and the ACC. This hypothesis was subsequently tested by measuring the spatial ACC in this participant using a longer duration stimulus. Two conditions were used, each with a change in stimulating electrode at the midpoint of the stimulus. The first condition was the standard stimulus, which consisted of biphasic pulses of 800 ms duration presented at 0.51 Hz. For the test condition, the stimulus had duration of 1400 ms and was presented at a rate of 0.4 Hz. The same stimulation level was used for both conditions. As can be seen in figure 8, the ACC is clearly seen in the test condition but not the standard condition for this participant. This shows that the sensitivity of the spatial ACC can be improved by altering stimulus characteristics and further work is needed to determine the optimal recording paradigm.

Disagreement between the objective and behavioural measurements also occurred when a significant spatial ACC response was recorded despite poor behavioural discrimination. This was observed for 9 measurements from 7 electrode pairs in 4 CI users. Previously we hypothesized that the presence of these ‘false positive’ recordings indicates the potential to develop accurate discrimination. The findings of this longitudinal study suggest that this is indeed the case. Electrode pairs with an objective pass were more likely to achieve a behavioural pass than electrode pairs with an objective fail. In 6 out of 7 electrode pairs with a ‘false positive’ ACC, a behavioural pass was achieved at a later date. Interestingly for participant S2, the ACC for electrode pair 2-3 was consistently present from 1 week onwards but a behavioural pass was only achieved at 12 months after switch-on.

Tremblay et al. (1998) also showed that changes in electrophysiological measurements can precede changes in behavioural performance. In their study, NH participants were trained to discriminate stimuli that differed in voice onset time. Four out of ten participants showed a significant MMN prior to changes in identification ability. Similarly, Trautwein et al. (1998) measured duration discrimination thresholds with behavioural and MMN measurements in CI users. The MMN threshold was found to be smaller than the behavioural threshold in 6/8 cases suggesting the MMN is a more sensitive measure of discrimination. The greatest disparity between objective and behavioural measures was seen in pre-lingually deafened adults. In our study, 3 out of 4 of the participants with ‘false positive’ ACC recordings had pre- or peri-lingual onset deafness. Only one participant had post-lingual onset deafness – although this participant had profound deafness for 10 years, the duration of bilateral hearing loss was 57 years. Early onset deafness and a long duration of hearing loss, are likely associated with a longer time course for auditory learning and could underlie the fact that stimulus change can be encoded without being perceived in certain individuals. Further confirmation of this finding is required from longitudinal studies, but our data suggest that the ACC may precede the development of accurate behavioural responses and this may make it particularly useful from a clinical point of view.

4.5 Clinical Implications

This study provides evidence for auditory plasticity in adult CI users, including individuals with early onset and long durations of deafness. This capacity of the auditory system to accommodate may underlie the fact that good results can be achieved in these groups (Lundin et al., 2014; Waltzman et al., 2002). Factors such as deafness onset and duration, in themselves, should therefore not be considered contraindications to implantation. The time course for change may vary widely between CI users and we found that processing of even simple stimuli continued to improve up to 1 year after switch-on in poorer performers. This raises the possibility of accelerating auditory accommodation with focused training. Indeed, studies in CI populations have shown that training, over as little as 4 weeks, can result in marked improvements in auditory performance, even after long periods of passive use of the speech processor (Fu and Galvin, 2008).

It is not yet clear what type of training approach will yield the most benefit in CI users. Fu et al. (2005a) showed that a ‘bottom up approach’ with phonetic contrast training resulted in significantly improved vowel, consonant and sentence recognition in adult CI users. Similarly, Fu and Galvin (2008), reported that electrode discrimination training in a pre-lingually deafened adult CI user, resulted in improved electrode discrimination as well as consonant and vowel recognition. Fu et al. (2005b), found that vowel contrast training but not sentence training in CI simulations with NH listeners led to improved vowel recognition with spectrally shifted speech. The authors suggest that developing phoneme recognition is particularly important in congenitally deaf late-implanted adults who must develop a ‘central speech template’. ‘Bottom-up’ training approaches, using electrode or phonetic contrasts, may therefore be particularly appropriate for poor performers in order to optimize performance as quickly as possible.

The results of this study also have potential implications for CI programming. CI channel deactivation has been employed as a strategy to reduce channel interactions and improve performance. The decision to deactivate electrodes has been based on performance on behavioural tasks including electrode discrimination (Zwolan et al., 1997), pitch ranking (Saleh et al., 2013; Vickers et al., 2016) and modulation detection (Garadat et al., 2013). Based on the results of this and other studies, two points are noteworthy. Firstly, it is important to understand the temporal dynamics of performance on psychophysical tasks if they are to be used to guide interventions. If behavioural performance can improve over long periods of time, then remapping procedures such as electrode deactivation, should not be performed prematurely. Secondly, it may be beneficial to measure auditory processing objectively with measures such as the ACC and MMN, as behavioural performance can lag behind objective measurements. If, for example, an electrode pair cannot be discriminated behaviourally but is encoded in the auditory pathway, then providing auditory training is likely to be more appropriate than deactivating electrodes. To this end we suggest that the ACC is a clinically useful tool, which enables objective assessment of auditory processing and accommodation. This objective measure is expected to be particularly useful for young children and adults in whom behavioural testing is challenging.

5. CONCLUSIONS

In this study we provide behavioural and electrophysiological evidence for improvements in discrimination ability in CI users over time. This is paralleled by improvements in speech perception. The ability of the auditory system to accommodate to electrical stimulation through the CI underlies the excellent outcomes that this technology yields. This process of change is slower and more limited in certain individuals and targeted therapies to exploit auditory plasticity may help improve hearing performance further.

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FIGURE CAPTIONS

Figure 1. Schematic of the stimuli used for measuring the spatial ACC. Stimuli consisted of 800ms biphasic electrical pulses at 1000 pulses per second with a change in stimulating electrode at the midpoint of the stimulus. The reference electrode is shown in red and the test electrode is shown in blue.

Figure 2. Changes in behavioural electrode discrimination scores over time. The broken lines show the mean electrode discrimination score for each individual. Note that behavioural scores were only measured at 12 months in individuals who had not achieved a behavioural pass for all 4 electrode pairs by 6 months (S1, S2, S5, S6). Random noise has been added to the discrimination scores in order to improve data visualization.

Figure 3. Change over time in number of electrodes with a pass based on behavioural pass-fail rules. The maximum score that can be achieved at any time point is 4 corresponding to the number of electrode pairs tested. The broken lines represent individual data. Behavioural scores were only measured at 12 months in individuals who had not achieved a behavioural pass for all 4 electrode pairs by 6 months (S1, S2, S5, S6). Random noise has been added to the behavioural pass score in order to improve data visualization.

Figure 4. Change in the mean spatial ACC amplitude over time. The broken lines show the mean ACC amplitude for each individual. The solid line shows the mean amplitude across all participants with error bars representing the standard error of the mean. Data at channel FCz are presented.

Figure 5. Example of cortical response development in participant S4 electrode pair 1-2. (A) At 1 week after switch-on, the spatial ACC is absent and there is a behavioural fail. (B) By 3 months after switch-on, there is a large spatial ACC response associated with a behavioural pass. The spatial ACC has been highlighted in red. Behavioural scores and the Hotelling-T2 (HT2) p values are indicated on each panel. The time windows used to detect positive and negative peaks (P1, N1, and P2) are shown in pink and blue, respectively. Scalp voltage maps for automatically detected peaks are displayed, with black lines representing isopotential contour lines. The horizontal lines correspond to the level of residual noise. Data at channel FCz are presented.

Figure 6. Examples of cortical responses where there was an objective ACC pass despite a behavioural fail. The participant ID, electrode pair, test time point and corresponding behavioural score are shown above each panel. Data are presented at a representative fronto-

central channel that is indicated on each panel along with the Hotelling-T2 (HT2) p value. The time windows used to detect positive and negative peaks (P1, N1, and P2) are shown in pink and blue, respectively. The horizontal lines correspond to the level of residual noise.

Figure 7. Change in speech perception over time. The broken lines show data for individual participants and the solid black lines shows the mean across participants with error bars representing the standard error of the mean. Random noise has been added to speech scores in order to improve data visualization.

Figure 8. Spatial ACC recordings using stimuli of varying durations for electrode pair 4-5 in participant S11. Stimuli consisted of biphasic pulses at 1000 pps with a change in stimulating electrode at the midpoint of the stimulus. (A) Standard condition with stimuli of 800 ms duration presented at 0.51Hz. (B) Modified stimulus with duration of 1400 ms and presentation rate of 0.4 Hz. Hotelling-T2 (HT2) p values are shown above each panel. Data are presented at channel FCz. The time windows used to detect positive and negative peaks (P1, N1, and P2) are shown in pink and blue, respectively. The horizontal lines correspond to the level of residual noise.

TABLES

Participant	Age	Sex	Ear	Communication	Duration profound hearing loss (years)	Deafness onset	4F-PTA non CI ear (dB HL)	Electrode
S1	51	M	R	oral	10	Post-lingual	116	Mid Scala
S2	50	F	R	oral + sign	50	Pre-lingual	115	Mid Scala
S3	42	F	L	oral	18	Post-lingual	118	Mid Scala
S4	48	M	L	oral	46	Pre-lingual	115	1J
S5	47	F	L	oral	42	Peri-lingual	103	Mid Scala
S6	68	F	L	oral	10	Post-lingual	100	Mid Scala
S8	51	F	R	oral	5	Post-lingual	96	Mid Scala
S9	48	M	L	oral	1	Post-lingual	113	Mid Scala
S10	80	M	L	oral	10	Post-lingual	78	Mid Scala
S11	65	F	L	oral	2.5	Post-lingual	98	Mid Scala

Table 1. demographic details of participants. F= female, M= male, R = right, L= left, 4F-PTA = four-frequency pure tone average, CI = cochlear implant.

Subject	Electrode	Original score at MC level and date	Retest score at same level	Date of retesting	Re-loudness balanced
S2	2-3	45%, 1 week	85%	16 months	No
	3-4	60%, 1 week	85%		Yes
S4	1-2	60%, 1 week	95%	20 month	No
	4-5	70%, 1 week	95%		No
S5	2-3	40%, 1 week	100%	16 months	No
	3-4	60%, 1 week	100%		No
	4-5	55%, 1 week	75%		Yes
		55%, 3 months	80%		Yes
S6	2-3	75%, 1 week	75%	15 months	No
		50%, 3 months	80%		No
	3-4	50%, 1week	55%		No
		65%, 3 months	75%		No
S11	1-2	70%, 1 week	100%	12 months	No

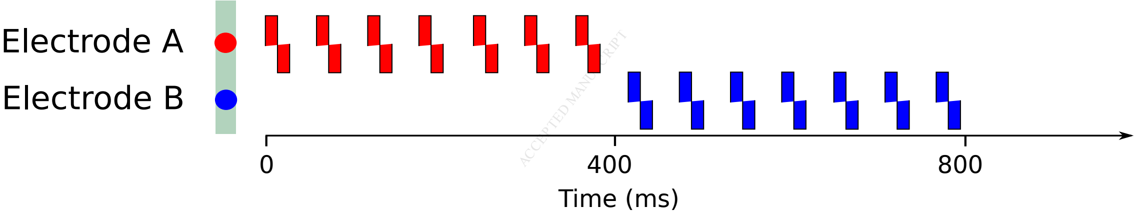
Table 2. Details of electrodes that went from a behavioural fail to a behavioural pass during the study. Original scores when a behavioural fail was achieved as well as re-test scores at a later time point with the same levels are shown. MC = most comfortable.

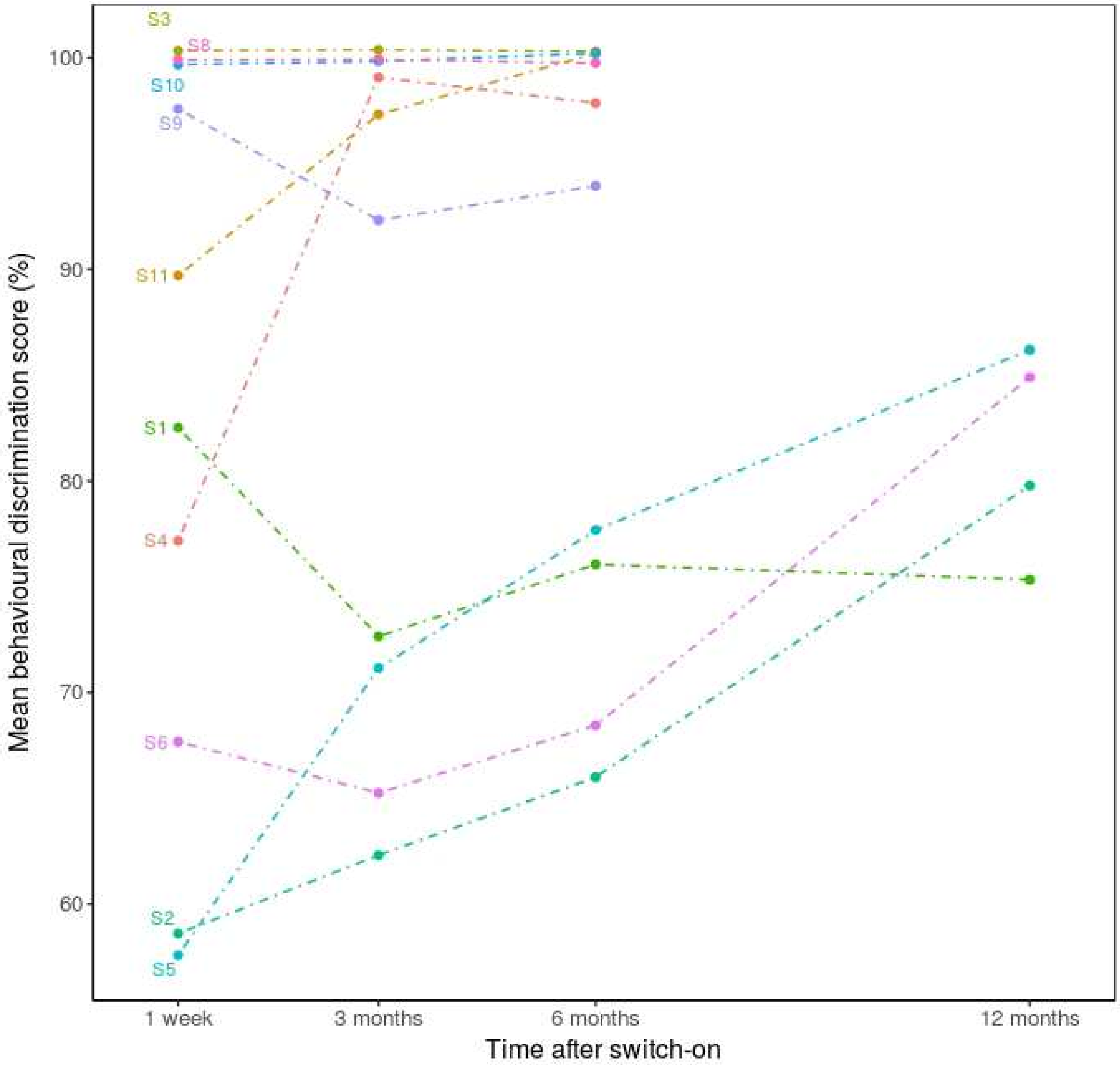
Date	Objective pass-behavioural pass	Objective fail-behavioural fail	Objective pass-behavioural fail	Objective fail-behavioural pass	Total agreement (/40)
1 week	21	13	2	4	34
3 months	26	9	2	3	35
6 months	25	5	5	5	30

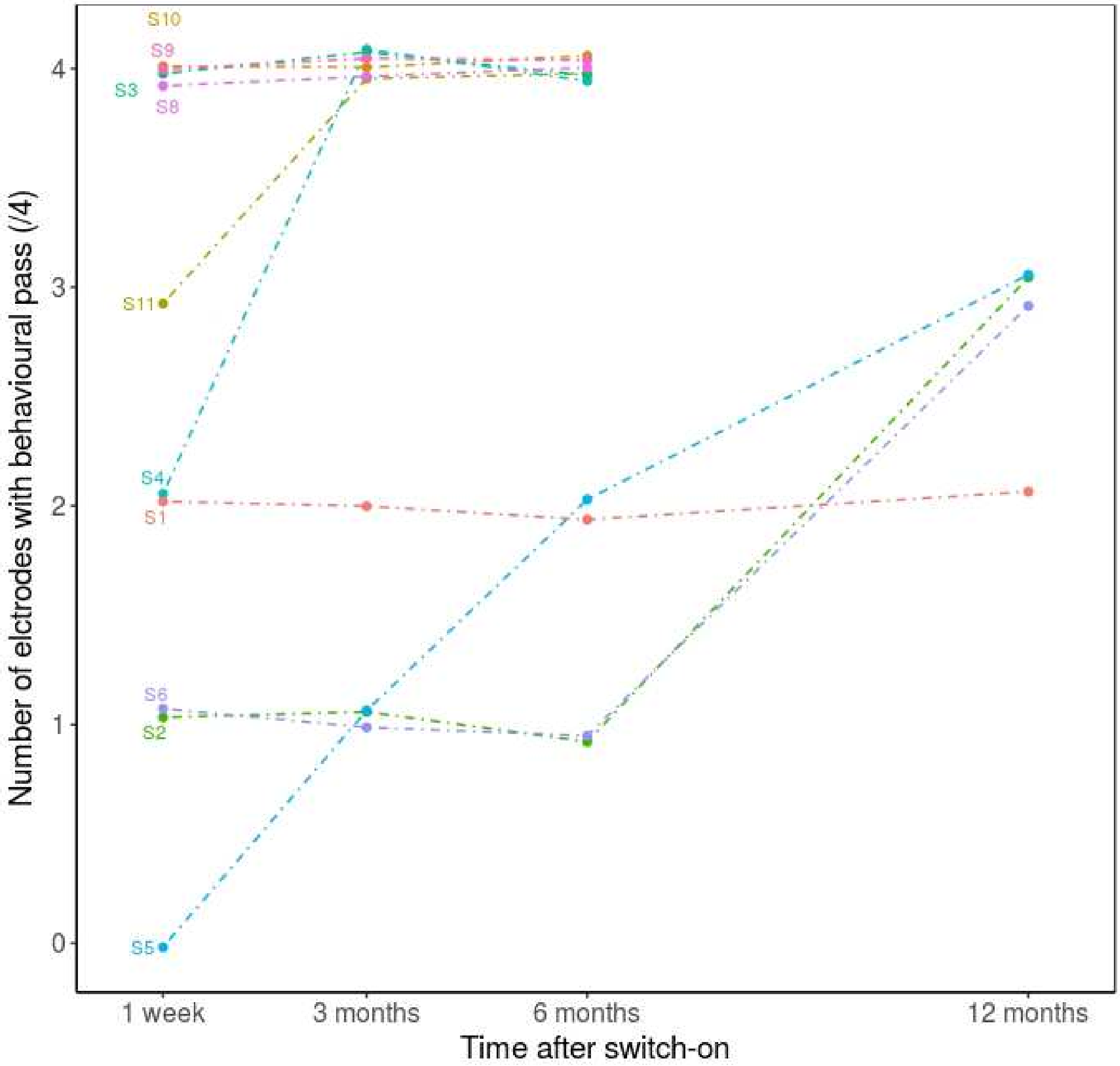
Table 3. Agreement between objective and behavioural pass-fail criteria for electrode discrimination at different time points.

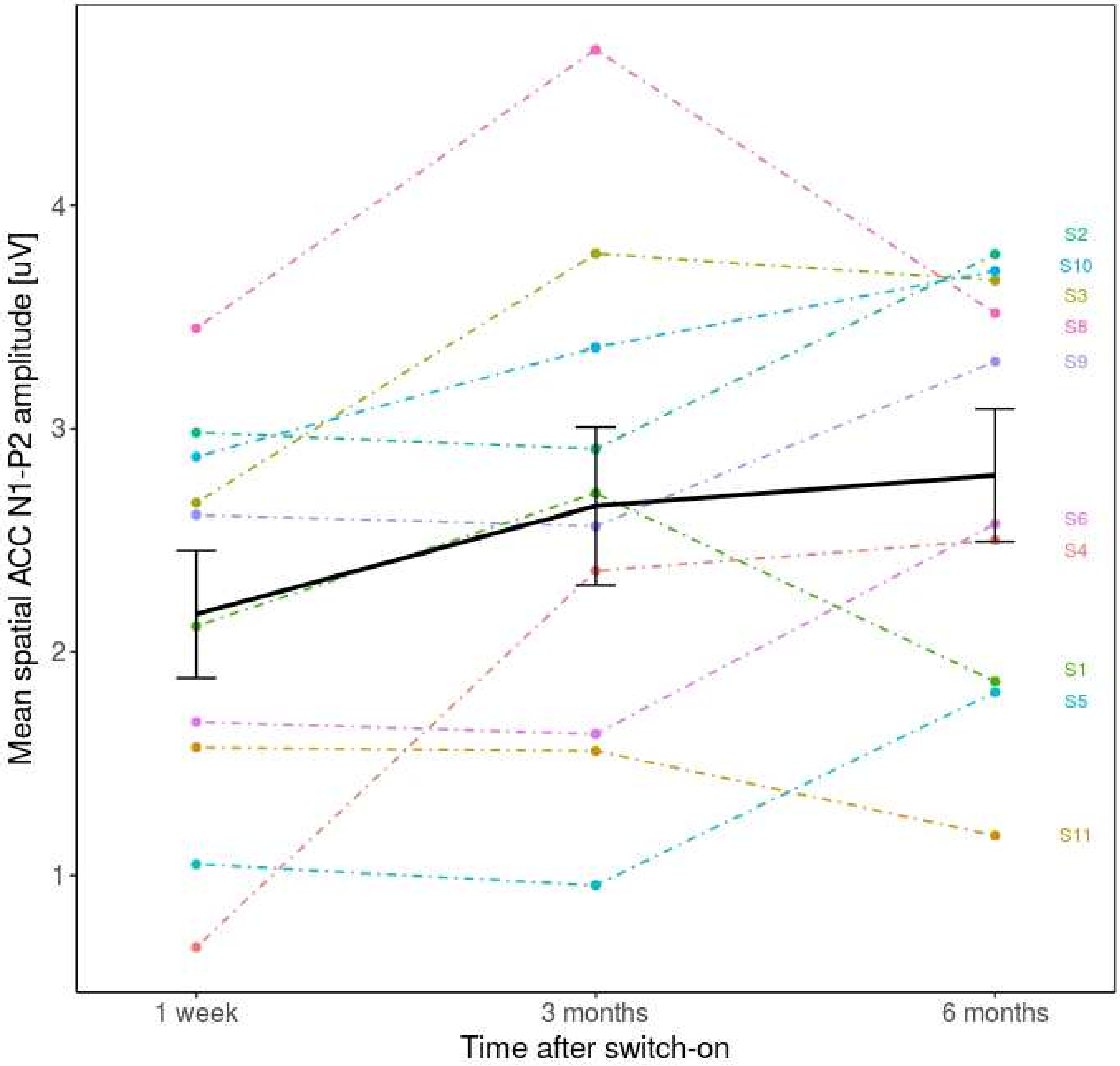
Subject and electrode	Date objective pass first achieved	Date behavioural pass first achieved	Behavioural scores (%)			
			1W	3M	6M	12M
S2 1-2	6M	NA (fail at 12M)	30	55	60	55
S2 2-3	1W (and at 3M and 6M)	12M	45	55	45	85
S2 3-4	6M	12M	60	40	60	80
S4 4-5	1W	3M	70	100	100	NA
S5 2-3	3M	6M	40	70	85	NA
S5 4-5	6M	12M	55	55	50	85
S6 2-3	6M	12M	75	50	55	90

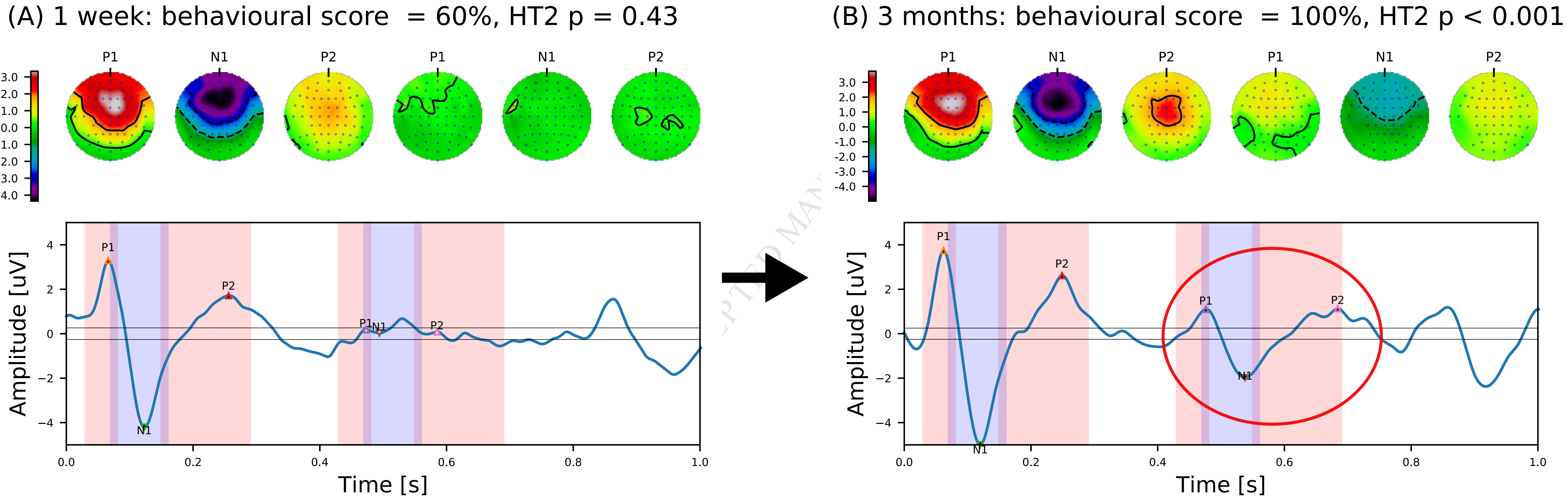
Table 4. Details of electrodes in which the objective ACC occurred despite a behavioural fail. 1W = 1week, 3M = 3 months, 6M = 6 months, 12M = 12 months and NA = not applicable.

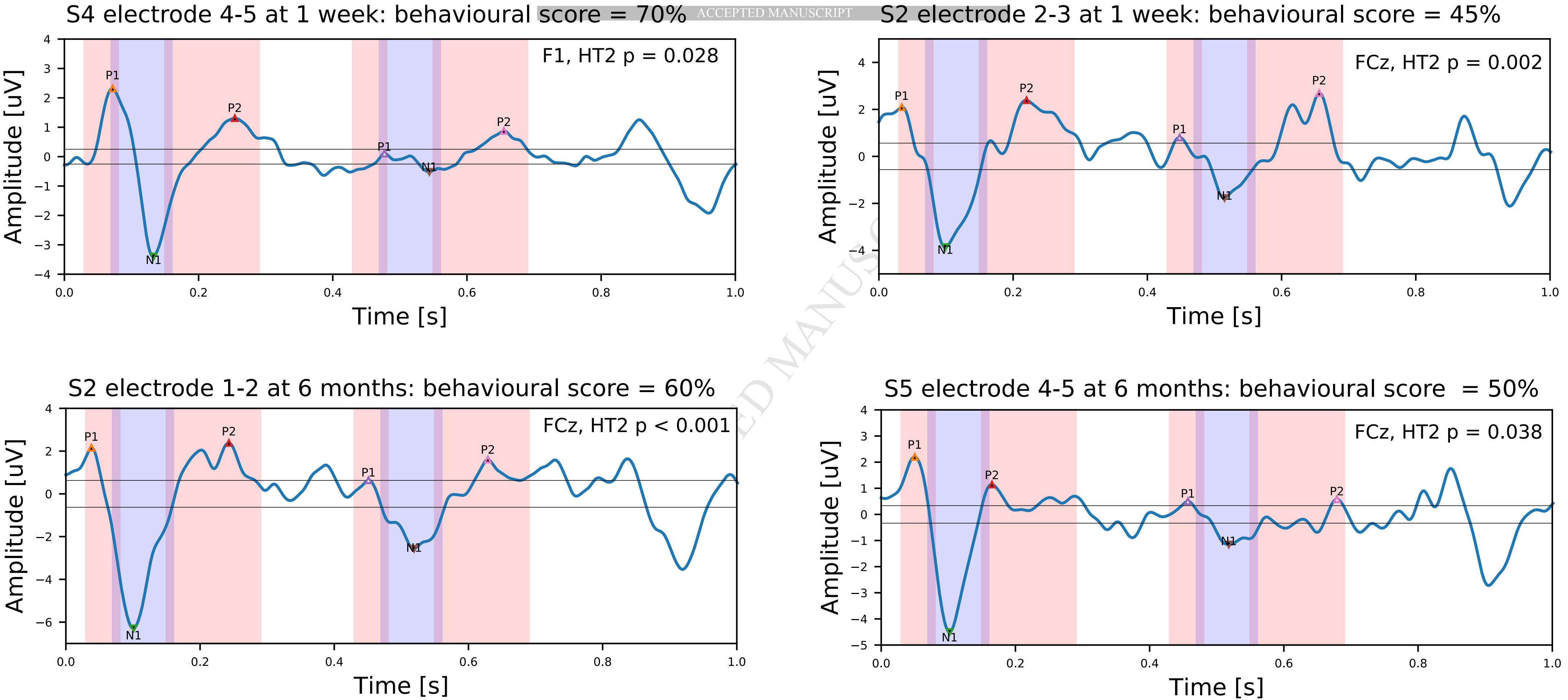

Electrode A
Electrode B
0
400
800
Time (ms)

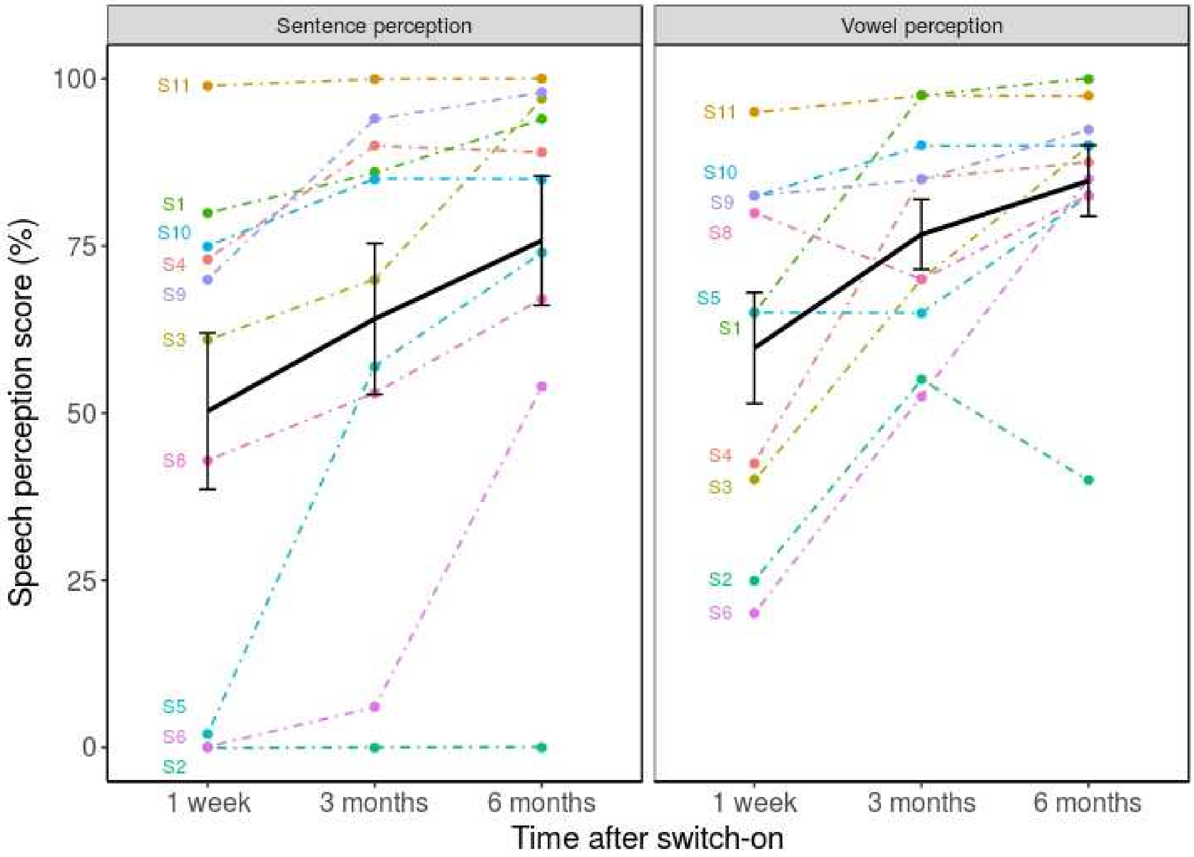

S3
S8
S10
S9
S11
S1
S4
S6
S2
S5
100
90
80
70
60
Mean behavioural discrimination score (%)
1 week
3 months
6 months
12 months
Time after switch-on

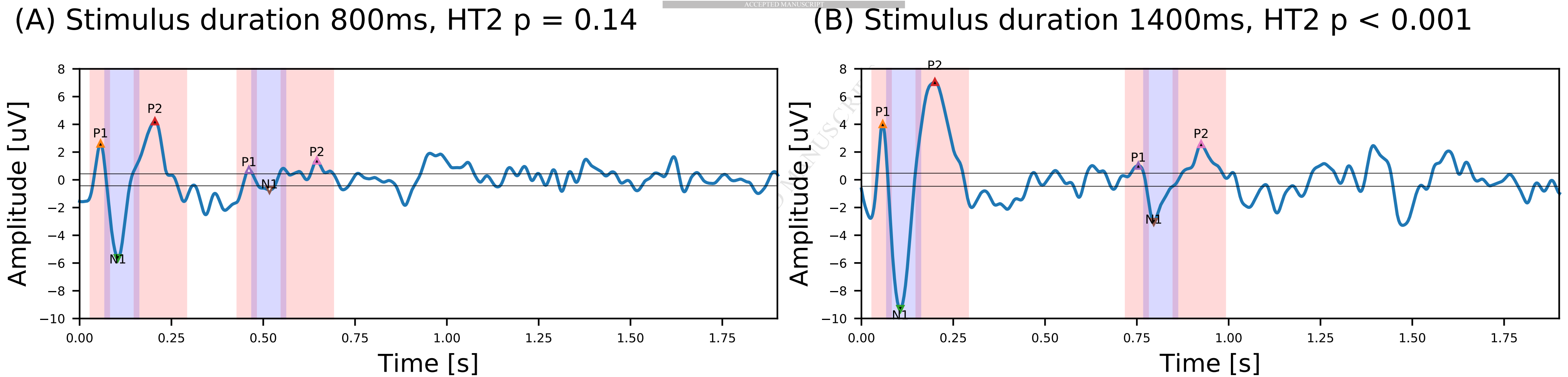

S10
S9
S3
S8
S11
S4
S1
S6
S2
S5
Number of elctrodes with behavioural pass (/4)
0
1
2
3
4
1 week
3 months
6 months
12 months
Time after switch-on


Mean spatial ACC N1-P2 amplitude [uV]
4
3
2
1
S2
S10
S3
S8
S9
S6
S4
S1
S5
S11
1 week
3 months
6 months
Time after switch-on


(A) 1 week: behavioural score = 60%, HT2 p = 0.43
(B) 3 months: behavioural score = 100%, HT2 p < 0.001
P1
N1
P2
P1
N1
P2
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
Amplitude [uV]
Time [s]
4
2
0
−2
−4
0.0
0.2
0.4
0.6
0.8
1.0


S4 electrode 4-5 at 1 week: behavioural score = 70%
F1, HT2 p = 0.028
P1
N1
P2
P1
N1
P2
Amplitude [uV]
Time [s]
4
3
2
1
0
−1
−2
−3
−4
0.0
0.2
0.4
0.6
0.8
1.0
S2 electrode 2-3 at 1 week: behavioural score = 45%
FCz, HT2 p = 0.002
P1
N1
P2
P1
N1
P2
Amplitude [uV]
Time [s]
4
2
0
−2
−4
0.0
0.2
0.4
0.6
0.8
1.0
S2 electrode 1-2 at 6 months: behavioural score = 60%
FCz, HT2 p < 0.001
P1
N1
P2
P1
N1
P2
Amplitude [uV]
Time [s]
4
2
0
−2
−4
−6
0.0
0.2
0.4
0.6
0.8
1.0
S5 electrode 4-5 at 6 months: behavioural score = 50%
FCz, HT2 p = 0.038
P1
N1
P2
P1
N1
P2
Amplitude [uV]
Time [s]
4
3
2
1
0
−1
−2
−3
−4
−5
0.0
0.2
0.4
0.6
0.8
1.0


Sentence perception
Vowel perception
Speech perception score (%)
100
75
50
25
0
S11
S1
S10
S4
S9
S3
S8
S5
S6
S2
S11
S10
S9
S8
S5
S1
S4
S3
S2
S6
1 week
3 months
6 months
1 week
3 months
6 months
Time after switch-on



(A) Stimulus duration 800ms, HT2 p = 0.14

(B) Stimulus duration 1400ms, HT2 p < 0.001

Highlights

- Electrode discrimination ability improves with hearing experience in CI users.
- There is marked inter-individual variability in the pattern of change over time.
- The ACC has a strong relationship with behavioural electrode discrimination.
- In certain cases, the ACC can precede accurate behavioural discrimination.