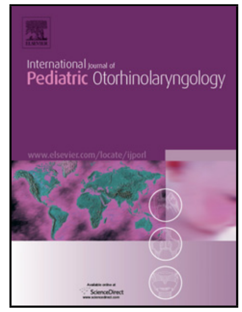

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Electrophysiological evidence for altered visual, but not auditory, selective attention in adolescent cochlear implant users

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Abstract

Objective: Selective attention fundamentally alters sensory perception, but little is known about the functioning of attention in individuals who use a cochlear implant. This study aimed to investigate visual and auditory attention in adolescent cochlear implant users.

Methods: Event related potentials were used to investigate the influence of attention on visual and auditory evoked potentials in six cochlear implant users and age-matched normally-hearing children. Participants were presented with streams of alternating visual and auditory stimuli in an oddball paradigm: each modality contained frequently presented 'standard' and infrequent 'deviant' stimuli. Across different blocks attention was directed to either the visual or auditory modality.

Results: For the visual stimuli attention boosted the early N1 potential, but this effect was larger for cochlear implant users. Attention was also associated with a later P3 component for the visual deviant stimulus, but there was no difference between groups in the later attention effects. For the auditory stimuli, attention was associated with a decrease in N1 latency as well as a robust P3 for the deviant tone. Importantly, there was no difference between groups in these auditory attention effects.

Conclusion: The results suggest that basic mechanisms of auditory attention are largely normal in children who are proficient cochlear implant users, but that visual attention may be altered. Ultimately, a better understanding of how selective attention influences sensory perception in cochlear implant users will be important for optimising habilitation strategies.

1. Introduction

The maturation of neural systems is contingent upon sensory experience, particularly during infancy. Alterations to sensory input during developmental 'critical periods,' when the brain is rapidly undergoing change, can fundamentally impact the functional organisation of the cortex [1-2]. For example, in the absence of hearing higher-order areas of the auditory cortex can be recruited to process visual information [3-5]. While such cross-modal plasticity may convey a processing advantage for visual information, this re-organisation of the latent auditory system can compromise the hearing restoration benefits provided by a cochlear implant (CI) [6]. In addition to plasticity, however, sensory perception is fundamentally shaped by selective attention. Selective attention refers to neural mechanisms that filter incoming sensory signals, boosting neural and behavioural responses to relevant stimuli and suppressing responses to irrelevant events [7-8]. Moreover, converging evidence suggests that attention also acts to guide plasticity, highlighting which neural circuits should undergo modification [9]. Attention should therefore be critical to learning to use a CI, but little is known about the functioning of selective attention in implant users. Here, we use electroencephalography (EEG) to investigate visual and auditory attention in children with a CI.

Numerous studies have shown that early access to sound is associated with a normalisation of auditory cortical development, as indexed by various EEG components. Sharma and colleagues [10-11] found that early-implanted (<3.5 years old) children's P1 latency quickly decreases to resemble that found in normally-hearing children, while neural responses in later implanted children remain less mature. Indeed, enduring alterations in auditory P1 latencies are observed if implantation occurs after seven years of age [10-11, for a review see 12]. The outcomes of these studies show that the input provided by an implant is sufficient for normal development of the central auditory system. These observations of normalised neural responses are consistent with functional outcomes that have linked earlier implantation with better speech perception abilities [for a review, see 13]. Identifying sensitive periods for auditory development has driven an urgency to implant children at earlier ages, with congenitally deaf infants now receiving prostheses as early as six months of age. When implanted early and given appropriate habilitation and support, CI recipients generally achieve good speech perception abilities in quiet conditions. Nevertheless, social and noisy environments (e.g. school rooms, playgrounds, shopping centres, etc.) can still present perceptual challenges to these children.

Selective attention plays a fundamental role in sensory perception, especially in noisy environments or when stimuli are degraded. Mechanisms of attention allow us to focus on task-relevant sensory information and ignore irrelevant events, and can be deployed voluntarily according to task demands (termed ‘top-down’ attention) or captured involuntary by highly salient stimuli (‘bottom-up’ attention)[7]. Deaf individuals (with and without a CI) have been shown to have some enhanced visual skills that are likely the result of both cross-modal plasticity between the visual and auditory system, as well as changes in visual attention [14]. Typically, no differences have been found between hearing and non-hearing groups’ in visual acuity, as measured in low-level perceptual tasks that alter contrast sensitivity, motion velocity and sensitivity, brightness and the temporal resolution of stimuli [15-19]. But more consistent between-group differences have been observed under conditions of selective attention and/or processing of peripherally located and salient items [20-22]. These outcomes have been explained in terms of a deafness-induced spatial redistribution of attention to the periphery, which may allow for monitoring the environment in the absence of hearing. Importantly, changes in visual attention may contribute to the known variability in speech perception performance of CI users. For example, it has been shown that auditory word recognition performance in non-proficient CI users (relative to proficient performers and normally hearing individuals) deteriorates in the presence of highly salient and moving visual stimuli [23].

The aim of our study was to determine if visual and auditory attention differentially affects information processing in a group of adolescent CI recipients and age-matched normally-hearing controls. Using event-related potentials (ERPs) we investigate the influence of attention on both early, perceptual processing (the N1 event-related potential) and later more cognitively-related processing of visual and auditory information (P3-related activity). Further, in both modalities responses to frequently occurring ‘standard’ stimuli and rare and salient ‘deviant’ events are recorded. Based on evidence that visual perception is altered by deafness, we predicted that while visual and auditory neural responses would be modulated by attention in both groups of children, attentional processes would be enhanced for deviant stimuli in CI users.

2. Materials and Methods

2.1 Participants

Participants were 12 children aged between 12 and 17.5 years. Six of these children were CI recipients (3 males) with a mean age of 14.45 years (range 12 to 16.9 years, *SEM* = .82 years) and six were children with normal hearing (NH, 2 males) that had a mean age of 15.5 years (range 13.9 to 17.5 years, *SEM* = .53 years). There was no difference between the ages of CI and NH children ($t_{10} = -1.09$, $p = .303$). The procedures of this study were approved by The University of Queensland Medical Research Ethics Committee. Parents provided written informed consent for their children's participation in the experiment.

Children with CIs were recruited from Hear and Say (Auchenflower, Brisbane, Australia), a paediatric auditory-verbal cochlear implant centre. Five children had been diagnosed as having bilateral profound sensorineural hearing loss at birth and another child at 12 months of age. The clinical details of these children are shown in Table 1. The speech perception abilities of CI children were determined from a review of their clinical test results, which included open- and closed-set tests. Speech perception scores were assigned to each child according to the Categories of Auditory Performance Index [24], which has nine hierarchic classifications (numbered 0-8). Higher scores reflect better speech perception abilities, with a score of 8 indicating an ability to perceive speech very well through audition alone in both quiet and noisy conditions. For the ear used during the experiment children in the present study had scores of 6, which indicates very good speech perception abilities in quiet conditions (open-set accuracy of ≥75%), or 5, which denotes good speech perception abilities in quiet conditions (>50% but <75% accuracy). Children with bilateral cochlear implants were tested using the first implant to be fitted and the other implant was removed, as was any aiding device in the non-implanted ear.

For all children speech perception was better in the tested (first implanted) ear (see Table 1). Normally hearing children were recruited through a university newsletter. All parents reported their children as having no cognitive or attentional impairments and to have normal (or corrected-to-normal) visual acuity.

2.2 Stimuli

As shown in Figure 1, participants were presented with alternate visual and auditory stimuli. For each modality there was a frequently presented 'standard' stimulus and infrequently presented 'deviant' and 'target' stimuli. The visual stimuli had five vertical sinusoidal gratings (3.0° x 2.9°) that were arranged at each corner and in the centre of a grey display (RGB: 128, 128, 128). The corner gratings were located diagonally from the centre grating at 8° of visual angle [as per 20]. The gratings on the standard stimulus had a spatial frequency of .99 cycles/degree and were black (0, 0, 0) and grey (128, 128, 128; see Figure 1). Unique to the target (relative to the standard stimulus) was the centre grating, which had either a reduced (.67 cycles/degree) or increased (1.7 cycles/degree) spatial frequency. The deviant stimulus differed from the standard in that the corner gratings were coloured blue (0, 0, 64) and grey (128, 128, 128) and appeared to move rightward at a velocity of .96°/120 ms. Apparent movement was achieved by replacing the initial image (presented for 40 ms) with two other images (for 40 ms each) whose corner gratings were temporally advanced. All visual stimuli were presented for 120 ms. The mean luminance of the black/grey and blue/grey gratings was 5.65 cd/m^2 (Minolta II Colour Meter). A black (0,0,0) asterisk of 0.52° visual angle was used as a central fixation point, but was occluded by the visual stimuli when present.

Stimuli were presented on a CRT monitor at a resolution of 1024 x 768 pixels and a refresh rate of 100 Hz, which was positioned 77 cm in front of the participant.

Auditory stimuli were 1000 Hz (standard and target) or 2000 Hz (deviant) pure tones. During the practice blocks it was established that all children were able to hear these tones. The standard and deviant tones were presented for 120 ms. Targets differed from the standard stimulus in their duration: one longer and the other shorter than the standard (see Figure 1). Target duration was determined individually for each child using a titration task (see 2.4 Procedure). All tones had a rise and fall time of 6 ms and were presented free field from speakers located immediately to the left and right of the monitor, with an intensity of ~70 dB SPL at the ear (Brüel and Kjaer sound meter, Type 2205).

2.3 Visual and auditory attention tasks

Alternating visual and auditory stimuli (comprising standards, deviants and targets) were presented with an interstimulus interval of 680 ms and across different blocks attention was directed to either the visual or auditory modality by having children detect targets in that modality. The visual attention task was to identify when the centrally-located grating changed to have 'less' or 'more' bars and the auditory attention task was to identify when the duration of the tone changed and became shorter or longer. Participants reported these target stimuli as quickly and accurately as possible by pressing one of two buttons located on the left and right of a response box, using their thumbs.

The visual and auditory attention tasks were presented in separate blocks, the order of which was partially counterbalanced across participants in an ABAB and BABA arrangement. Each task consisted of 1200 stimulus presentations; 600 presentations per modality. Stimuli were pseudo-randomly presented in an oddball-like manner where the standard, deviant and target stimuli were presented at a probability of P =.78, P = .15, and P = .07, respectively. This resulted in 468 standards, 90 deviants and 42 targets in each modality. A minimum of two standards from the same modality always preceded the deviant and target stimuli. The target stimuli occurred on average every 20 seconds (± 10 seconds) to help participants' maintain attention toward the correct modality. The duration of each block was eight to nine minutes.

2.4 Procedure

After the EEG cap was fitted and electrode impedances reduced participants completed practice blocks of the auditory and visual attention tasks, respectively. Three pairs of target-tones were incorporated into the auditory practice. These were labelled 'easy' (20 and 320 ms duration tones), 'moderate' (40 and 200 ms), or 'difficult' (60 and 180 ms) based on the disparity between the duration of the target and that of the standard tone (120 ms). The target pair used in the experiment was the pair that the participant had most difficulty discriminating but which she/he correctly identified 80% or more of the time. This method was used to ensure comparable behavioural performance between the CI users and NH children in the auditory attention task. Target stimuli were not entered into the EEG analysis. All CI children and one NH child completed the easiest discrimination (20/320 ms) pair. Of the remaining NH children, three completed the most difficult (60/180 ms) discrimination and two the 40/200 ms discrimination. Each practice block took approximately four minutes to complete.

During the experiment proper, task and fixation instructions were reiterated at the start of each block. Participants were told that their eye movements would be monitored using a closed circuit television (CCTV) camera that was positioned above the monitor. Fixation was assured by observing the online trace of the horizontal electro-oculograph (HEOG) channel and data containing abnormal movements were subsequently removed from the analysis (see 2.5 Electroencephalography recording and data processing). During training children were given feedback about whether or not their EEG trace indicated eye movement. Rest duration between blocks was determined by the participant and total testing time was about one hour.

2.5 Electroencephalography recording and data processing

EEG was acquired using a Neuroscan SynAmps2 ™ amplifier and a 64 channel electrode (Ag/AgCl) cap. The EEG data was recorded continuously at a sampling rate of 10 KHz and bandpass filtered (DC - 2.5 KHz). Electrode placement corresponded with the International 10-10 electrode positioning system. Bipolar vertical and horizontal EOG was recorded from electrodes placed above the supra-orbital ridge of the left eye and below the left eye, and adjacent to the outer canthi of both eyes. Recordings were referenced online to the vertex and an extra electrode placed on the tip of the nose served as an offline reference. Electrodes immediately above the CI recipients' radio frequency coil and near their over-the-ear microphone were not used. This generally excluded lateral centro-parietal electrodes on the hemisphere of the implant. Electrode impedance was reduced to below 10 KOhms. Eye blink artefacts were corrected using the Semlitsch et al. [25] algorithm, a function incorporated into the Neuroscan program.

The EEG continuous data were filtered offline using a bandpass filter (0.05-30 Hz; 12 dB roll off) and then divided into epochs beginning 100 ms pre-stimulus and ending 800 ms post-stimulus. These epochs were baseline corrected using the pre-stimulus period. Trials on which baseline to peak EOG amplitude exceeded 100 μV or baseline-to-peak drift exceeded 60 μV were excluded from averaging. An ICA-based method was used to remove a cochlear-elicited artefact from the data of one child that onset with auditory tones and that was evident on implant side electrodes [26]. The acquisition rate of the averaged waveforms was then reduced to 1000 points per second.

2.6 Data analysis

To investigate differences in behavioural performance between the groups the number of correct responses (hits) and false alarms were used to calculate detection sensitivity (d′), where d′=[z(hits)-z(false alarms)] and z(p) is the inverse of the cumulative normal distribution. Instances where p = 1 or 0 were approximated as 1-1/(2N) or 1/(2N), respectively, where N is the number of trials [27]. Independent samples t-tests were used to compare both d′ and reaction time data of CI users and NH children in the visual and auditory attention tasks. For the EEG data, analysis was conducted using ERPs elicited by the standard and deviant stimuli; ERPs to target stimuli were discarded due to there being insufficient numbers, the potential for contamination by response-related activity and, for auditory targets, differences in tone duration across participants. Visual and auditory ERPs were assessed at N1 epochs (visual: 100-200 ms, auditory: 100- 260 ms) using peak amplitude and latency, and P3 (visual and auditory: 300-500 ms) using mean amplitude. Peak amplitude was defined as the largest negative deflection occurring within the N1 interval and latency as the time instant at which that peak occurred.

Visual N1 ERPs were analysed at midline parieto-occipital electrode sites (average of POz and Oz) and auditory N1 ERPs at midline fronto-central electrodes (averaged over Fz and FCz). The data were submitted to mixed ANOVA with the repeated-measures factors attention (visual, auditory) and stimulus (standard, deviant) and the between-subject factor group (CI, NH) for each modality. To elucidate attentional effects at the later, more cognitive-related potentials, P3 difference waves were created by subtracting ERPs to non-attended stimuli from those of attended stimuli within each modality (i.e., visual responses: attend visual *minus* attend auditory; auditory responses: attend auditory *minus* attend visual). Because this subtraction involves ERPs generated by the same physical stimulus, any differences can be attributed to attention-related effects [28-29]. This ERP difference wave, termed here as 'Pd' (positive difference) was analysed at midline fronto-central sites (averaged over Fz, FCz, Cz). Mean amplitudes were submitted to a mixed ANOVA with the factors stimulus (standard, deviant) and group (CI, NH) for each modality. The Geisser-Greenhouse correction was used to correct for violations of the assumption of the homogeneity of covariance for within-subjects factors. Alpha was set at .05 and the Bonferroni correction was used to compensate for familywise Type 1 error.

3. Results

3.1 Behavioural data

Children's attention was directed toward the visual or auditory stimuli by having them monitor for and detect targets in the relevant modality. Both CI and NH children correctly detected a high percentage of targets in the visual (CI: M = 92.62 %, SEM = 3.52 %; NH: M = 87.99 %, SEM = 5.84) and auditory (CI: M = 79.26 %, SEM = 8.06 %; NH: M = 89.16 %, SEM = 2.5 %) conditions. Sensitivity (d′) for detecting targets was very high and did not differ between the groups for either the visual (CI: *M* = 4.49, *SEM* = 0.32; NH: *M* = 4.58, *SEM* = 0.24; %; t (10) = -0.23, $p > .05$) or auditory (CI: *M* = 3.46, *SEM* = 0.40; NH: *M* = 4.24, *SEM* = 0.14; t (10) = -1.82, $p > .05$) tasks. Similarly, there was no difference between the groups' reaction times to the visual targets (CI: *M* = 594 ms, *SEM* = 31 ms; NH: *M* = 566 ms, *SEM* = 31 ms; t (10) = .65, $p > .05$). However, reactions times to auditory targets did differ across groups, with CI children being significantly slower at detecting targets than NH children (CI: *M* = 912 ms, *SEM* = 55 ms; NH: *M* = 670 ms, *SEM* = 41 ms; t (10) = 3.55, $p < .01$).

3.2 Visual evoked potentials

The grand average ERP waveforms evoked by the visual stimuli in the visual and auditory attention conditions are shown in Figure 2 for midline frontal (FCz), central (CPz) and parietal (POz) electrodes. Prominent at the posterior sites was a P1/N1/P2 complex in which the N1 deflection peaked at 156 ms. Also apparent in both groups waveforms, but commencing at about 300 ms was a P3 deflection for the deviant stimulus when it was presented in the visual attention condition. The NH children also had a (smaller) P3 to the deviant under the auditory attention condition.

We firstly investigated whether attention modulated the obligatory N1 ERP at posterior electrode sites (averaged over POz and Oz). Mixed ANOVA (attention x stimulus x group) using peak amplitude revealed a significant main effect for attention (F (1,10) = 15.16, $p = .003$, $\eta^2_p = .60$) and a significant attention x group interaction (F (1,10) = 6.37, $p = .03$, $\eta^2_p = .39$). No reliable differences were found between standard and deviant N1s (F (1,10) = 1.8, $p = .21$) or for other interactions. The difference between groups in the effect of attention on N1 (attention x group interaction) is illustrated in Figure 3, which shows that while both groups' N1 response (collapsed across standard and deviant stimuli) was largest for attended compared to non-attended visual stimuli, this effect was enhanced for CI compared to NH children. Follow-up pair-wise t-tests confirmed a significant N1 difference between attended and non-attended stimuli for CI children, (t (5) = 4.02, p = .01), but no similar effect for NH children (t (5) = 1.14, p = .31). Unlike N1 amplitude, analysis of N1 peak latencies did not identify any significant differences across factors or between groups (attention F (1,10) = .001, p = .98, stimulus F (1,10) = 2.11, p = .18, group F (1,10) = .11, p = .75). The N1 mean latencies for the CI and NH groups, collapsed across all factors were 154.79 ms (*SEM* = 8.31 ms) and 157.94 (*SEM* = 4.56 ms), respectively.

As previously described, attentional effects at the P3 epoch were isolated by subtracting ERPs for stimuli occurring during the auditory task from those for the same stimuli appearing during the visual task (averaged across Fz, FCz, Cz). The resultant peak (labelled Pd) is presented in Figure 4A and revels that the P3 attention effect for the deviant stimulus was larger for the CI than the NH group. There is also a (smaller) Pd for the standard in the CI group (see Figure 4A, B). ANOVA revealed, however, that the Pd was not significantly modulated by group or stimulus (group F (1,10) = 1.73, p = .22; stimulus F (1,10) = 2.82, p = .12; stimulus x group F (1,10) = 1.00, p = .34).

3.3 Auditory evoked potentials

The grand average ERP waveforms evoked by the auditory stimuli in the auditory and visual attention conditions are shown in Figure 5 for midline frontal (FCz), central (CPz) and parietal (POz) electrodes. Evident in these, and also in each of the individual children's waveforms (data not shown), is an N1 deflection peaking around 150-170 ms. A prominent P3 deflection is also apparent for the deviant in the auditory attention condition. As expected, these auditory deflections are largest at fronto-central locations.

Mixed ANOVA revealed that N1 peak amplitudes (averaged over FZ and FCZ) were not reliably modulated by attention (F (1,10) = .35, p = .57), stimulus (F (1,10) = 1.32, p = .28) or group (F (1,10) = .86, p = .38), or interactions between these factors. However, analysis of N1 latency revealed significant main effects for attention (F (1,10) = 5.51, p = .047, η^2_p = .34) and stimulus (F (1,10) = 6.80, p = .03, η^2_p = .41). The N1 latency was shortest when attention was directed toward the auditory stimuli (attend auditory condition M = 158.33 ms, SEM = 8.23 ms; attend visual condition M = 166.46 ms, SEM = 9.98 ms). In addition, the N1 response elicited by the standard stimulus peaked earlier than that of the deviant (standard M = 155.46 ms, SEM = 8.61 ms; deviant M = 169.33, SEM = 10.03 ms).

The difference waveforms obtained by subtracting responses in the attend-visual condition from those in the attend-auditory condition are presented in Figure 6A, revealing a prominent deviant-driven Pd effect. Analysis of the mean Pd amplitude (see Figure 6B), confirmed a significant main effect for stimulus (F (1,10) = 10.07, p = .01, η^2_p = .50), with mean amplitudes for the deviant Pd being significantly more positive than those of the standard. There was no significant between-group difference (F (1,10) = .16, p = .70) or stimulus x group interaction (F (1,10) = .10, p = .76).

4. Discussion

This study investigated auditory and visual selective attention in CI users and age-matched NH children. Behavioural outcomes indicated that both groups of children attended to the correct modality, although CI users were significantly slower at responding to auditory targets. Both groups' early (N1) ERP responses to visual stimuli were enhanced with attention, but this effect was larger for CI children. Attending to the auditory modality was associated with a reduction in N1 latency and a Pd enhancement for the deviant compared to the standard tone for both groups.

4.1 Behavioural results

In this study alternating visual and auditory stimuli were presented and across experimental blocks a detection task directed children's attention toward either the visual or auditory modality. Performance on the visual task was very high and did not differ between the groups, suggesting that attention was successfully manipulated. The auditory attention task required children to detect target tones that differed in duration from the commonly occurring standard tone. Target tone duration was adjusted according to individual performance in a practice block to ensure that task difficulty was equated between the CI and NH groups. All children with a CI completed the task using the 'easy' target tones (i.e., those most different in duration from the standard tone), while all but one of the NH children completed the task using the much more difficult to discriminate tones. This procedure resulted in equal detection sensitivity (d′) between the groups, but reaction times were longer for the CI users. One contribution to this longer response time could be the longer duration tones presented to the CI users, as a decision about duration cannot be made until the sound has ceased. However, the extra 100-120 ms duration of the target tones detected by CI users[1] does not fully account for the 242 ms difference in average response times. Moreover, the longest duration target tone was paired with the shortest duration target (50% probability), so it could be argued that response time should be quicker for the latter sounds. Thus, the longer reaction times are instead likely to reflect an increased task-demand and cognitive effort required by CI users to complete the auditory detection task, despite the titration procedure. Critically, the behavioural results nonetheless confirm that both groups of children attended to the relevant modality.

4.2 ERPs and visual attention

In the present study visual ERPs were recorded whilst attention was directed to the visual or auditory modality. Inclusion of the deviant stimulus allowed us to also investigate differences in the way CI and NH children process salient, peripherally-located, task-irrelevant information. Based on evidence that processing of peripheral visual information is enhanced by deafness, and therefore potentially more distracting [4, 21-22, 30-31], we predicted that CI children's attentional responses to the deviant stimuli would be larger than those of NH children. However, we found that both groups' visual N1s were boosted by attention, and that responses did not differ for standard and deviant stimuli. This influence of attention on the N1 potential is similar to that reported in many

[1]Five of the six NH children completed the auditory task using target tones that were shorter by 120-140 ms (for the longer duration tone), and longer by 20-40 ms (for the shorter duration tone), than those detected by CI users.

studies using NH adults [32-33]. Interestingly, the overall influence of attention was enhanced in CI users compared to the NH children.

One explanation for these processing differences is that children with a CI rely more heavily on visual input than do their NH peers [34], possibly the result of the impoverished sound signal provided by an implant [35-36]. This added reliance may have driven improvements in the CI users' capacity to selectively attend to critical visual information (and ignore irrelevant visual information). This enhancement is despite the very good hearing (speech perception) abilities of the CI group, at least in quiet conditions. The high-level hearing abilities of the CI users in this study are probably the result of being implanted at a young age (between 1.3 and 3.9 years). Moreover, all children underwent auditory-verbal therapy, which emphasises learning to listen and, particularly during the initial stages of this intervention, discourages use of visual cues such as lip-reading or sign language. Despite this habilitation, the CI users in the present study appear to have enhanced early neural processing of visual information under conditions of selective attention. Presumably, early implantation in the children tested here precludes deafness-induced cross-modal plasticity as an explanation for the visual N1 effects. Moreover, increased recruitment of the auditory cortex to process visual information is typically associated with decrements in CI speech perception abilities [37-38], which is not a characteristic of our sample. Thus, the current results suggest that differences in visual processing between CI users and NH children are due, at least in part, to changes in selective attention, driven by the demand to adapt to the environment with impaired hearing.

An alternative explanation for the enhanced N1 in CI users is that they may have found the visual discrimination task more difficult, and so required extra resources to complete it. Recently Turgeon and colleagues [39] observed that CI compared to NH adults had higher visual discrimination thresholds for spatial frequency discrimination tasks; the stimuli used in their task were similar to those used here to manipulate visual attention. The authors of that study concluded that significant periods of progressive hearing loss experienced from birth or infancy (age at implantation ranged between 8 and 52) likely affected this 'low-level' visual ability, highlighting the complementary role that the auditory and visual systems might play in normal perceptual development. If our group of CI children found the visual task more demanding, then perhaps their enhanced visual N1s reflects an attentional boosting of the signal required to discriminate the targets. One caveat of this contention, however, is that there was no difference in behavioural performance between the CI and NH children.

In addition to the early visual effects, we hypothesised that the deviant stimulus would be associated with a later more cognitively-related P3 ERP, and that this effect would be enhanced for CI children. The novelty P3 effect is typically evoked by rare, salient and task-irrelevant deviants that are interspersed occasionally among attended stimuli (standard and target) in a three-stimulus oddball task, and it has been more commonly shown with auditory stimuli [40]. ERPs to the deviant did in fact elicit a P3 but attention appeared to modulate this effect differently across groups (see Figure 2). The deviant stimulus presented during the visual and auditory tasks elicited a P3 with relatively similar amplitudes for NH children. In contrast, for CI children the deviant elicited a prominent P3 but only when attention was directed toward the visual stimuli.

This difference could be expected if CI children found the auditory attention task more demanding, which could reduce processing of the irrelevant visual deviant [41]. To better compare responses to the deviant under differing attentional conditions, we calculated difference waves that confirmed that attention boosted CI children's P3 deviant response more than that of NH children (Pd effect; Figure 4). However, analysis of the Pd effect at midline fronto-central sites, where P3 novelty effects are typically observed [40, 42], revealed that it was not reliably modulated by stimulus type or group. Inspection of the individual children's visual Pds revealed that positive deflections were found for four of the CI children (mean amplitudes ranged between 6 μV and 16.4 μV) and three of the NH children (mean amplitudes ranged between 4 μV and 8.5 μV). These within- and between-group variances as well as the small sample size may have precluded a significant difference from emerging between the stimulus types and groups. As well as investigating this possibility, future research would benefit from also testing CI users with poorer speech perception abilities, who may rely more on visual input and therefore show greater differences in visual attention.

4.3 ERPs and auditory attention

Overall we did not find any differences in the influence of attention on auditory ERPs between CI users and NH children. The standard and deviant stimuli were 1000 Hz and 2000 Hz tones, respectively. ERPs were recorded to these tones when attention was directed to the auditory or visual stimuli. In both groups stimuli elicited a midline fronto-centrally located N1, the peak amplitudes of which were not reliably modulated by attention. However, attention significantly affected the latencies at which these deflections occurred, with N1s for stimuli in the attended condition peaking earlier compared to when attention was directed to the visual modality. Importantly, there was no difference between CI and NH children in this attention effect on N1 latency. Attention also did not differentially affect the latency of N1 for the standard and deviant stimuli. One reason for the lack of an attention-related modulation of N1 amplitude is that our auditory discrimination task was not sufficient to induce such an effect. Future research should determine if there is a more robust attentional effect on N1 amplitude when auditory stimuli are immersed in noise, a condition known to be more demanding for CI users and to more strongly engage attention. For bilaterally implanted children it would also be worthwhile to investigate the influence of attention on auditory ERPs using both implants (individually and together), especially where a difference exists in hearing ability across implants. In addition to an attention effect on N1 latency, analysis also revealed that both groups' standard-induced N1s (independent of attention) peaked significantly earlier than those of the deviant-induced N1s. This effect is likely the result of processing a familiar versus a novel and rare stimulus.

Although attention altered the latency but not the amplitude of the N1 potential elicited by the standard or deviant tone, attending to the auditory modality was associated with a robust P3 for the deviant stimulus. In the attend-auditory condition a prominent positive deflection was observed for both groups of children in the P3 epoch, as highlighted in the difference (Pd) waveforms (see Figure 6A). For both groups, this deviant-induced attention effect was found to be significantly enhanced compared to that for the standard. It has been reported previously that the auditory P3a was reduced in amplitude in (post-lingually deafened adult) CI users under 'passive' listening conditions [43]. This effect was taken to indicate that CI users are impaired in the registration of novel auditory events under non-attentive, but not attentive, conditions. Our results, obtained in a similar sized sample of younger CI users, do not support this contention. Importantly, visual attention was not controlled in that previous study (participants were required to read a book under the non-attentive condition), and it is therefore possible that changes in visual processing, cognitive demands and/or attention lead to the auditory P3 effects. In order to optimise the habilitation of CI users it will be important for future research to determine the conditions under which auditory processing may be impacted by changes in visual attention.

5. Conclusion

This study has shown that the influence of attention on visual and auditory neural processing is similar for adolescent CI users and age-matched normally-hearing children. Selective attention was shown to enhance early neural processing of visual and auditory stimuli (N1s) as well as later more cognitively oriented processing of visual and auditory deviants (Pd). The main between-group difference was that the visual N1 of CI users was boosted by attention more than that of NH children. This effect may be driven by an increased reliance on visual information by children with a CI. Future studies using experimental tasks that manipulate levels of background noise, processing load and the spatial distribution of stimuli, as well as recruiting participants with differing hearing (speech perception) abilities, may better identify how visual selective attention influences auditory neural responses and behaviour in CI users.

Conflict of Interests

The authors declare that they have no conflict of interests regarding the publication of this article.

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References

[1] E.I. Knudsen, Sensitive periods in the development of the brain and behavior, J. Cogn. Neurosci. 16 (2004) 1412-1425.

[2] P.K. Kuhl, Early language acquisition: cracking the speech code, Nat. Rev. Neurosci. 5 (2004) 831-843.

[3] D. Bavelier, H.J. Neville, Cross-modal plasticity: where and how?, Nat. Rev. Neurosci. 3 (2002) 443-452.

[4] E.M. Finney, I. Fine, K.R. Dobkins, Visual stimuli activate auditory cortex in the deaf, Nat. Neurosci. 4 (2001) 1171-1173.

[5] A. Kral, J. Tillein, S. Heid, R. Hartmann, R. Klinke, Postnatal cortical development in congenital auditory deprivation, Cereb. Cortex. 15 (2005) 552-562.

[6] D.S. Lee, J.S. Lee, S.H. Oh, S.K. Kim, J.W. Kim, J.K. Chung, et al., Cross-modal plasticity and cochlear implants, Nature 409 (2001) 149-150.

[7] M. Corbetta, G.L. Shulman, Control of goal-directed and stimulus-driven attention in the brain, Nat. Rev. Neurosci. 3 (2002) 201-215.

[8] E.I. Knudsen, Fundamental components of attention, Annu. Rev. Neurosci. 30 (2007) 57-78.

[9] P.R. Roelfsema, A. van Ooyen, T. Watanabe, Perceptual learning rules based on reinforcers and attention, Trends Cogn. Sci. 14 (2010) 64-71.

[10] A. Sharma, M.F. Dorman, A. Kral, The influence of a sensitive period on central auditory development in children with unilateral and bilateral cochlear implants, Hear. Res. 203 (2005) 134-143.

[11] A. Sharma, M.F. Dorman, A.J. Spahr, A sensitive period for the development of the central auditory system in children with cochlear implants: implications for age of implantation, Ear Hear. 23 (2002) 532-539.

[12] J.M. Johnson, Late auditory event-related potentials in children with cochlear implants: a review, Dev. Neuropsychol. 34 (2009) 701-720.

[13] A. Kral, A. Sharma, Developmental neuroplasticity after cochlear implantation, Trends Neurosci. 35 (2012) 111-122.

[14] J.C. Dahmen, A.J. King, Learning to hear: plasticity of auditory cortical processing, Curr. Opin. Neurobiol. 17 (2007) 456-464.

[15] R.G. Bosworth, K.R. Dobkins, Left-hemisphere dominance for motion processing in deaf signers, Psych. Sci. 10 (1999) 256-262.

[16] M. Bross, Residual sensory capacities of the deaf: a signal detection analysis of a visual discrimination task, Percept. Mot. Skills 48 (1979) 187-194.

[17] C.J. Brozinsky, D. Bavelier, Motion velocity thresholds in deaf signers: changes in lateralization but not in overall sensitivity, Brain Res. Cogn. Brain Res. 21 (2004) 1-10.

[18] E.M. Finney, K.R. Dobkins, Visual contrast sensitivity in deaf versus hearing populations: exploring the perceptual consequences of auditory deprivation and experience with a visual language, Brain Res. Cogn. Brain Res. 11 (2001) 171-183.

[19] E. Nava, D. Bottari, M. Zampini, F. Pavani, Visual temporal order judgment in profoundly deaf individuals, Exp. Brain Res. 190 (2008) 179-188.

[20] B.A. Armstrong, H.J. Neville, S.A. Hillyard, T.V. Mitchell, Auditory deprivation affects processing of motion, but not color, Cogn. Brain Res. 14 (2002) 422-434.

[21] D. Bavelier, C. Brozinsky, A. Tomann, T. Mitchell, H. Neville, G. Liu, Impact of early deafness and early exposure to sign language on the cerebral organization for motion processing, J. Neurosci. 21 (2001) 8931-8942.

[22] D. Bavelier, A. Tomann, C. Hutton, T. Mitchell, D. Corina, G. Liu, et al., Visual attention to the periphery is enhanced in congenitally deaf individuals, J. Neurosci. 20 (2000) RC93.

[23] F. Champoux, F. Lepore, J.P. Gagne, H. Theoret, Visual stimuli can impair auditory processing in cochlear implant users, Neuropsychologia 47 (2009) 17-22.

[24] J. Black, L. Hickson, B. Black, Defining and evaluating success in paediatric cochlear implantation--an exploratory study, Int. J. Pediatr. Otorhinolaryngol. 76 (2012) 1317-1326.

[25] H.V. Semlitsch, P. Anderer, P. Schuster, O. Presslich, A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP, Psychophysiology 23 (1986) 695-703.

[26] A. Hyvarinen, Fast and robust fixed-point algorithms for independent component analysis, IEEE Trans. Neural. Netw. 10 (1999) 626-634.

[27] N. A. MacMillan, C. D. Creelman, Detection Theory: A User's Guide, 2nd ed., Psychology Press, New York, (2004).

[28] K. Alho, D.L. Woods, A. Algazi, R. Naatanen, Intermodal selective attention. II. Effects of attentional load on processing of auditory and visual stimuli in central space, Electroencephalogr. Clin. Neurophysiol. 82 (1992) 356-368.

[29] D.L. Woods, K. Alho, A. Algazi, Intermodal selective attention. I. Effects on event-related potentials to lateralized auditory and visual stimuli, Electroencephalogr. Clin. Neurophysiol. 82 (1992) 341-355.

[30] M.W. Dye, D.E. Baril, D. Bavelier, Which aspects of visual attention are changed by deafness? The case of the Attentional Network Test, Neuropsychologia 45 (2007) 1801-1811.

[31] J. Proksch, D. Bavelier, Changes in the spatial distribution of visual attention after early deafness, J. Cogn. Neurosci. 14 (2002) 687-701.

[32] G.R. Mangun, Neural mechanisms of visual selective attention, Psychophysiology 32 (1995) 4-18.

[33] G.R. Mangun, S.A. Hillyard, S.J. Luck, Electrocortical substrates of visual selective attention, in: D.E. Meyer, S. Kornblum (Eds.), Attention and performance XIV: Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience, MIT Press, Cambridge, 1993, pp. 219-243.

[34] A.L. Giraud, C.J. Price, J.M. Graham, E. Truy, R.S. Frackowiak, Cross-modal plasticity underpins language recovery after cochlear implantation, Neuron 30 (2001) 657-663.

[35] J. Rouger, S. Lagleyre, B. Fraysse, S. Deneve, O. Deguine, P. Barone, Evidence that cochlear-implanted deaf patients are better multisensory integrators, Proc. Natl. Acad. Sci. U.S.A. 104 (2007) 7295-7300.

[36] E.A. Schorr, N.A. Fox, V. van Wassenhove, E.I. Knudsen, Auditory-visual fusion in speech perception in children with cochlear implants, Proc. Natl. Acad. Sci. U.S.A. 102 (2005) 18748-18750.

[37] M.E. Doucet, F. Bergeron, M. Lassonde, P. Ferron, F. Lepore, Cross-modal reorganization and speech perception in cochlear implant users, Brain 129 (2006) 3376-3383.

[38] H.J. Lee, A.L. Giraud, E. Kang, S.H. Oh, H. Kang, C.S. Kim, et al., Cortical activity at rest predicts cochlear implantation outcome, Cereb. Cortex. 17 (2007) 909-917.

[39] C. Turgeon, F. Champoux, F. Lepore, D. Ellemberg, Reduced visual discrimination in cochlear implant users, Neuroreport 23 (2012) 385-389.

[40] D. Friedman, Y.M. Cycowicz, H. Gaeta, The novelty P3: an event-related brain potential (ERP) sign of the brain's evaluation of novelty, Neurosci. Biobehav. Rev. 25 (2001) 355-373.

[41] N. Lavie, Distracted and confused?: selective attention under load, Trends Cogn. Sci. 9 (2005) 75-82.

[42] J. Polich, M.D. Comerchero, P3a from visual stimuli: typicality, task, and topography, Brain Topogr. 15 (2003) 141-152.

[43] W. Nager, T.F. Munte, I. Bohrer, T. Lenarz, R. Dengler, J. Mobes, et al., Automatic and attentive processing of sounds in cochlear implant patients - electrophysiological evidence, Restor. Neurol. Neurosci. 25 (2007) 391-396.

Figure Legends

Fig. 1. Visual and auditory stimuli. Participants were presented with an alternating stream of visual and auditory stimuli; both modalities contained frequently presented ‘standard’ (shown in the stream on the left) and infrequent ‘deviant’ and target events (insert). The deviant visual stimulus consisted of coloured, moving peripheral gratings (indicated by

arrows in the insert). Attention was manipulated by having participants discriminate targets in the relevant modality. Visual targets varied in the spatial frequency of the central grating, whereas auditory targets varied in duration according to performance during practice.

Fig. 2. Grand average waveforms elicited by the visual stimuli at midline electrodes. Black and grey lines show ERPs when attention was directed to the visual (Vis) or auditory (Aud) modality, respectively. Tick marks indicate 2 μV (vertical axis) and 100 ms (horizontal axis).

Fig. 3. Peak amplitudes of the visually-evoked N1 over midline posterior electrodes (averaged over POz, Oz). Responses are shown for the visual (Vis) and auditory (Aud) attention conditions collapsed across stimulus type for normal hearing (NH) children and cochlear implant (CI) recipients. For the CI users, but not the NH children, the peak amplitude of N1 was larger for visual stimuli appearing during the visual attention task than for those same stimuli appearing during the auditory attention task. Error bars represent *SEM*.

Fig. 4. Attention-related effects on endogenous visually-evoked potentials. (A) Grand average visually-evoked difference waves (attend-visual minus attend-auditory) over frontal electrodes (averaged over Fz, FCz, Cz) are shown for normally-hearing (NH) children and cochlear implant (CI) recipients for standard (Std) and deviant (Dev) stimuli. (B) Mean amplitude of the Pd (300 to 500 ms) did not differ across stimuli or groups. Error bars represent *SEM*.

Fig. 5. Grand average waveforms elicited by the auditory stimuli at midline electrodes. Black and grey lines show ERPs when attention was directed to the visual (Vis) or auditory (Aud) modality, respectively. Tick marks indicate 2 μV (vertical axis) and 100 ms (horizontal axis).

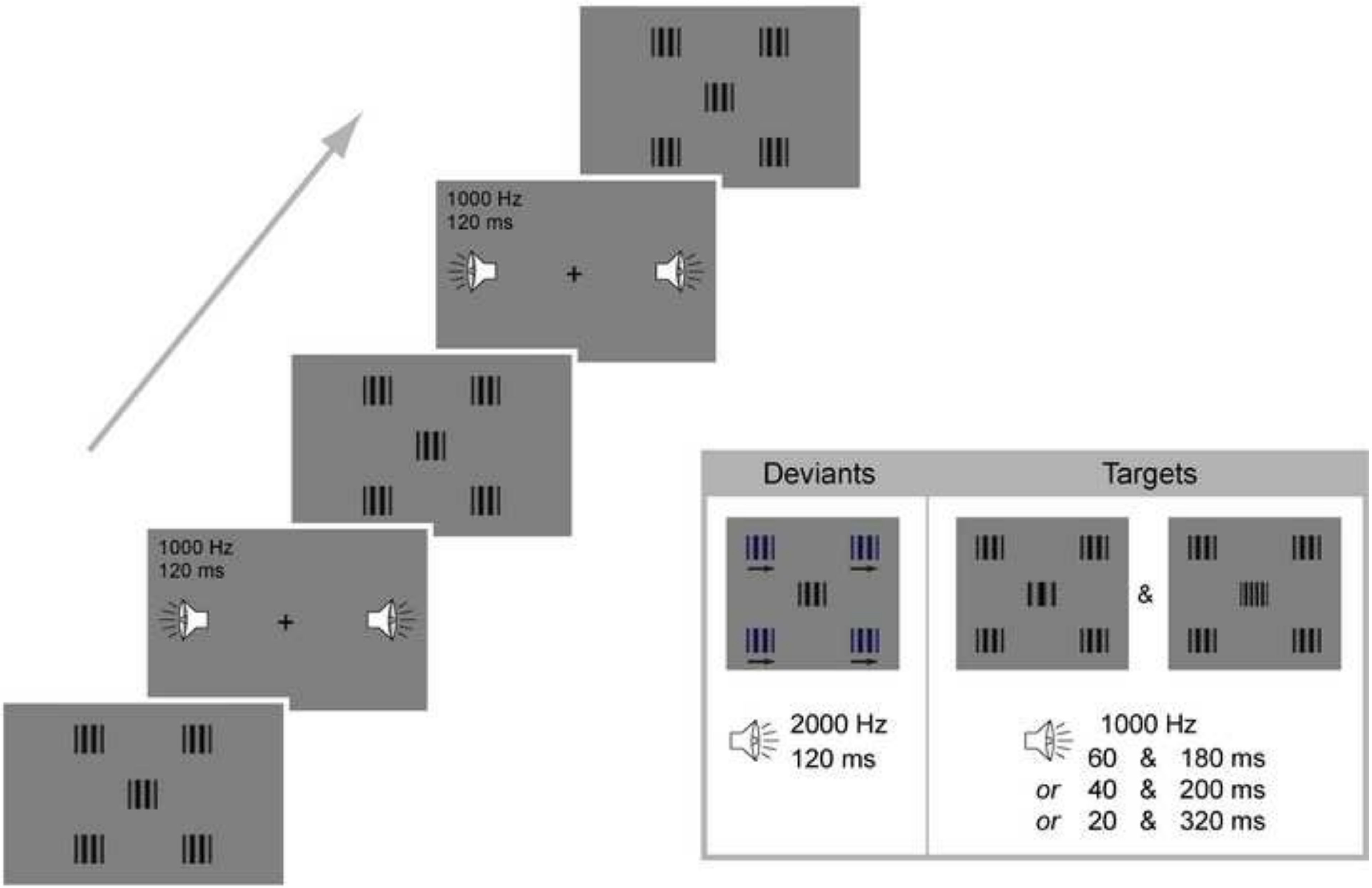
Fig. 6. Attention-related effects on endogenous auditory-evoked potentials. (A) Grand average auditory-evoked difference waves (attend-auditory minus attend-visual) over frontal electrodes (averaged over Fz, FCz, Cz) are shown for normally-hearing (NH) children and cochlear implant (CI) recipients for standard (Std) and deviant (Dev) stimuli. (B) Mean amplitude of the Pd (300 to 500 ms) differed across stimuli. Error bars represent *SEM*.

Table 1. Clinical demographics of cochlear implant (CI) users

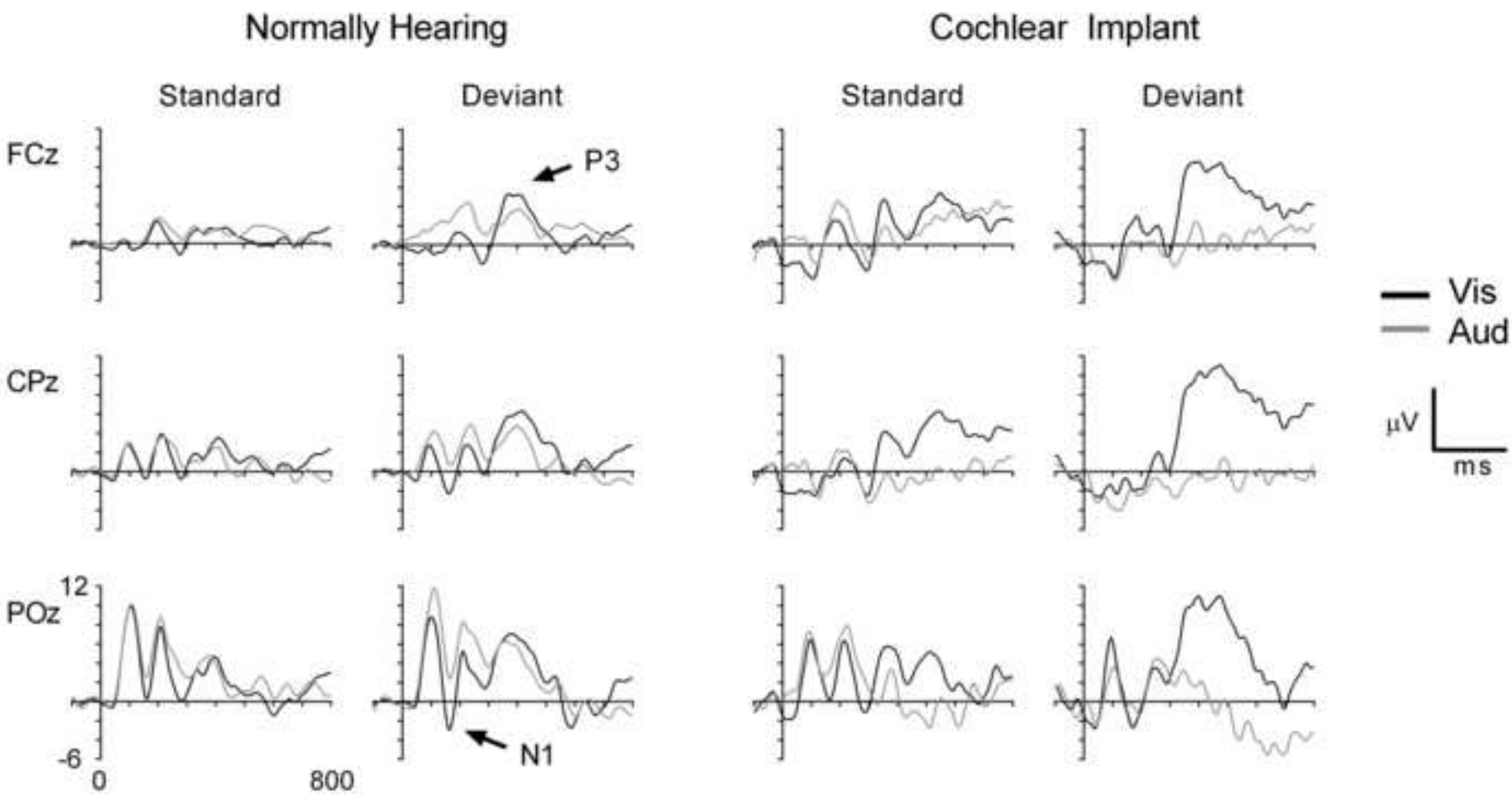
Subject	Age (yrs)	Gender	Age at onset of profound deafness (yrs)	Age at implantation (yrs)	CI side	Speech processor	Implant	Speech perception score (L)	Speech perception score (R)
1	13.7	M	Birth	2.1	L+R	Freedom	N24	5	6
2	12	M	1	1.9	L+R	Freedom	N24	4	5
3	16.9	F	Birth	1.7	L+R	Freedom	N22	4	5
4	12.5	M	Birth	1.3	L+R	Freedom	N24	2	6
5	15.6	F	Birth	3.9	R	Freedom	N24	-	6
6	16	F	Birth	2.7	L+R	Freedom	N24	5	2

Note: For children with bilateral CIs the ear tested is underlined, as is the speech perception score for that ear. Speech perception scores are shown for left (L) and right (R) ears and are based on the Categories of Auditory Performance Index (for details see section *2.1 Participants*). All children used a Cochlear Ltd implant and processor (type is shown for the ear tested).

Figure(s)



1000 Hz
120 ms
1000 Hz
120 ms
Deviants
Targets
&
2000 Hz
120 ms
1000 Hz
60 & 180 ms
or 40 & 200 ms
or 20 & 320 ms


Normally Hearing
Cochlear Implant
Standard
Deviant
Standard
Deviant
FCz
CPz
POz
P3
N1
12
-6
0
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Vis
Aud
µV
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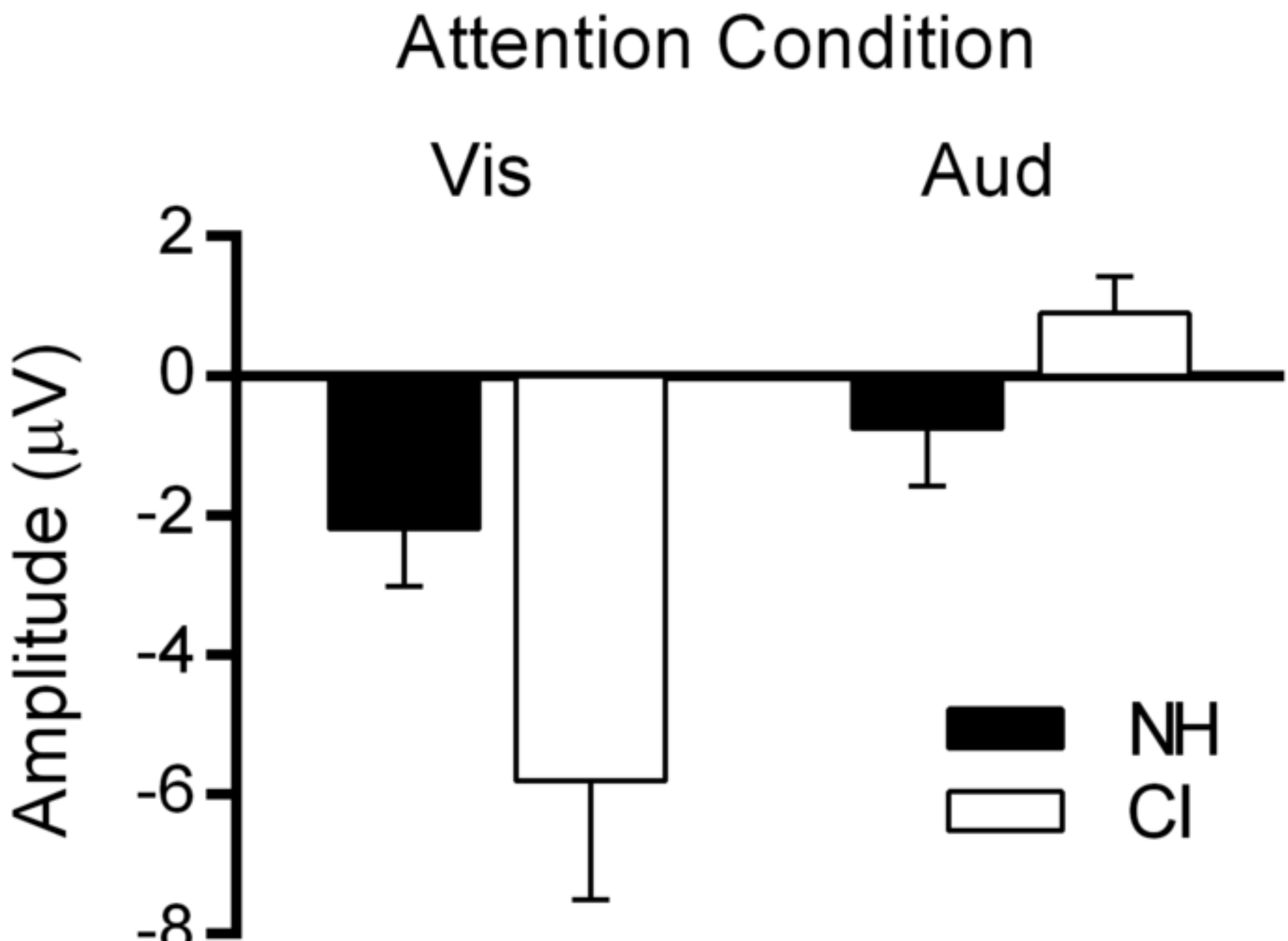
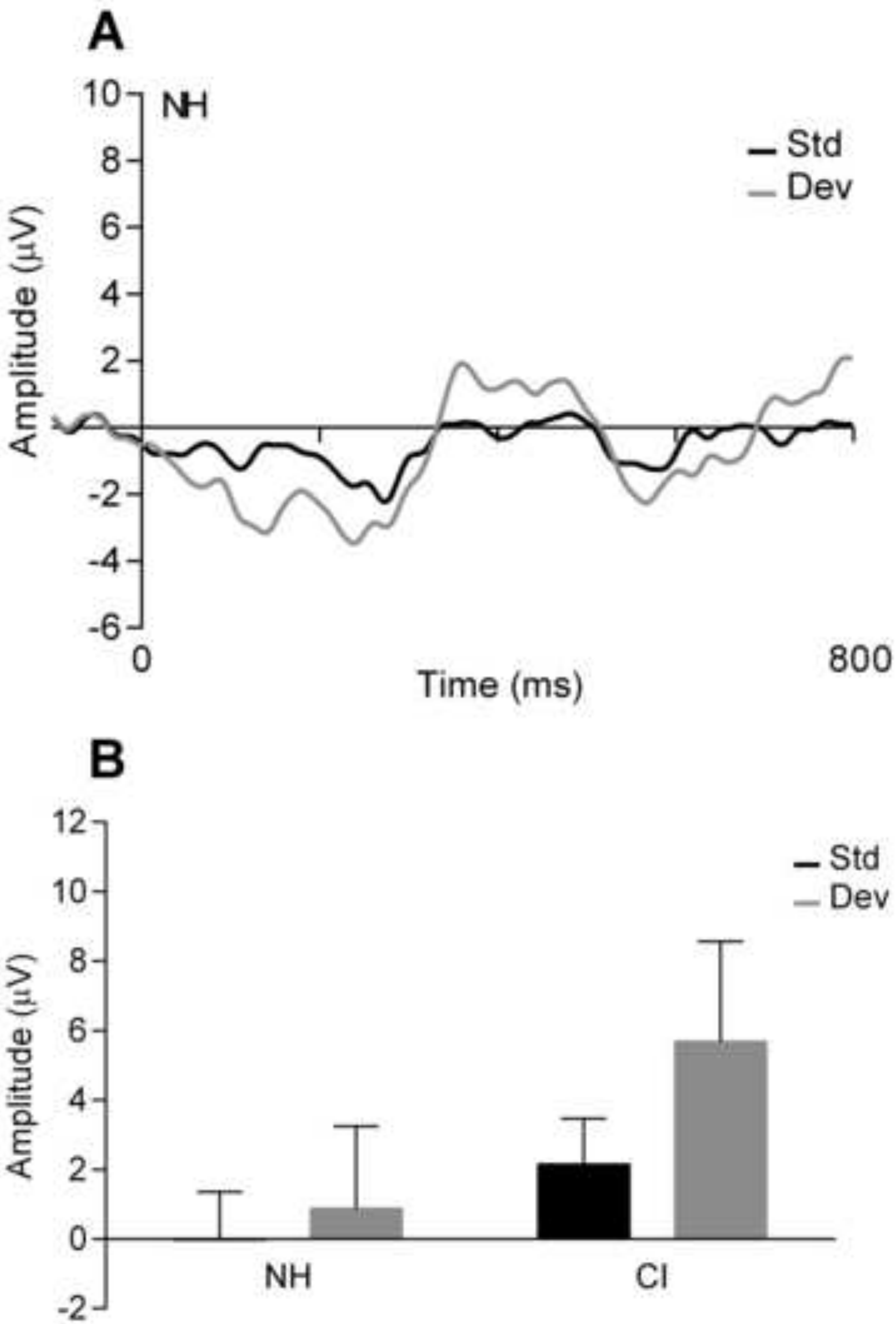
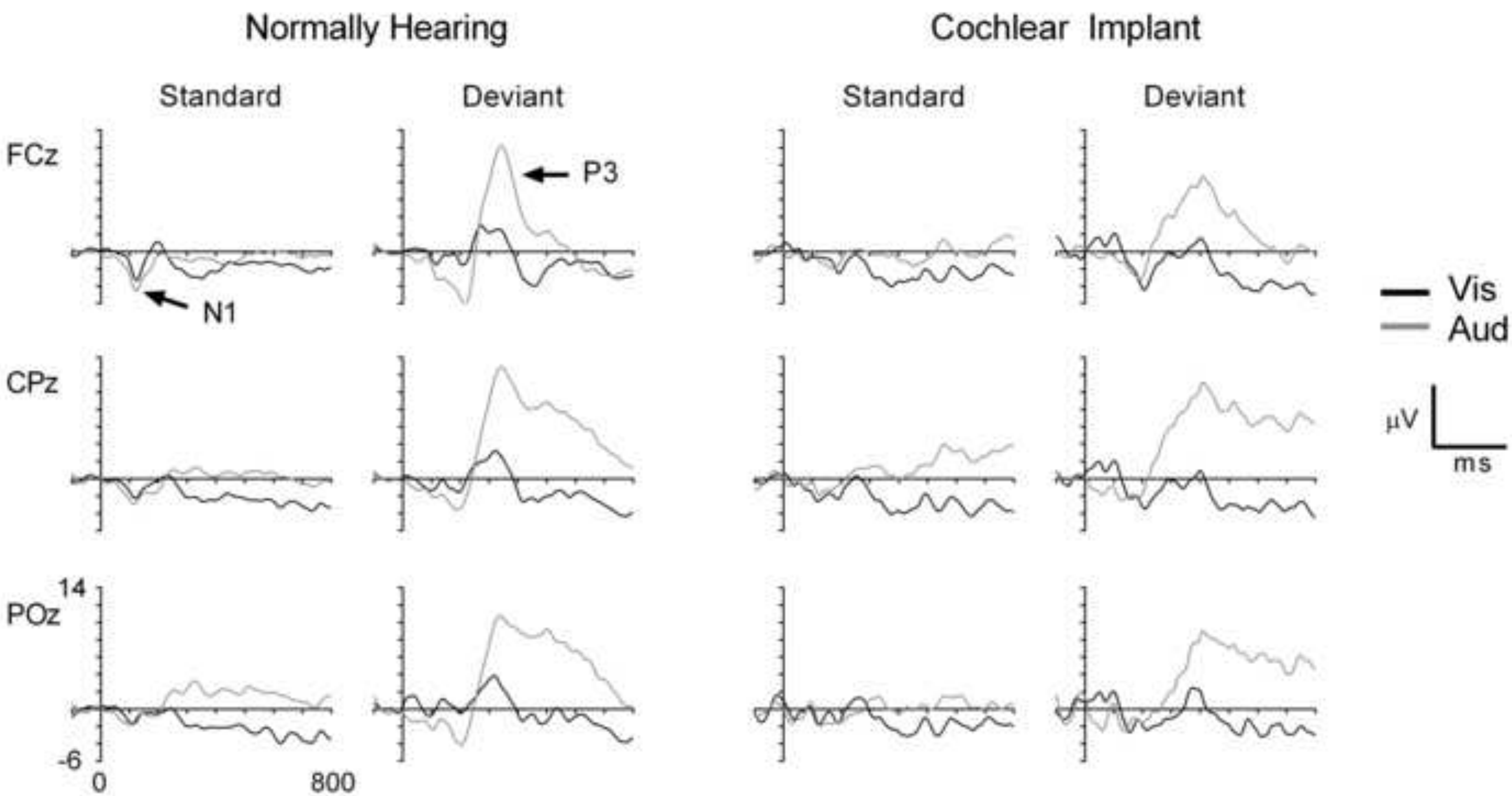

Attention Condition
Vis
Aud
Amplitude (μV)
2
0
-2
-4
-6
-8
NH
CI

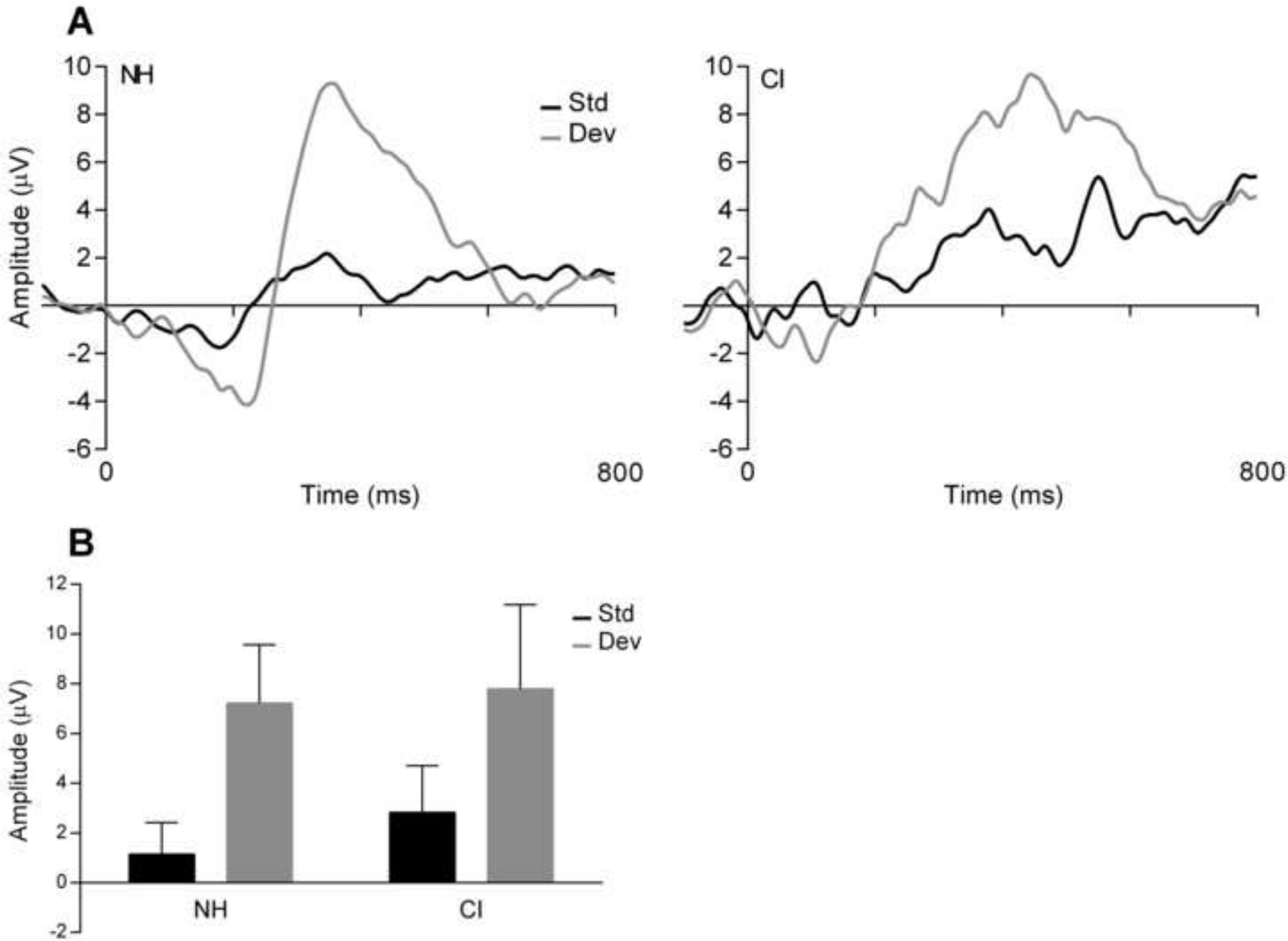

A
NH
CI
Std
Dev
Amplitude (μV)
10
8
6
4
2
-2
-4
-6
0
800
Time (ms)
B
12
10
8
6
4
2
0
-2
NH
CI

Figure(s)



Normally Hearing
Cochlear Implant
Standard
Deviant
Standard
Deviant
FCz
CPz
POz
P3
N1
14
-6
0
800
Vis
Aud
µV
ms

Figure(s)



A
NH
Std
Dev
CI
Amplitude (µV)
10
8
6
4
2
-2
-4
-6
0
800
Time (ms)
B
Std
Dev
12
10
8
6
4
2
0
-2
NH
CI