Peripheral hearing loss reduces the ability of children to direct selective attention during multi-talker listening

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Abstract

Restoring normal hearing requires knowledge of how peripheral and central auditory processes are affected by hearing loss. Previous research has focussed primarily on peripheral changes following sensorineural hearing loss, whereas consequences for central auditory processing have received less attention. We examined the ability of hearing-impaired children to direct auditory attention to a voice of interest (based on the talker's spatial location or gender) in the presence of a common form of background noise: the voices of competing talkers (i.e. during multi-talker, or "Cocktail Party" listening). We measured brain activity using electro-encephalography (EEG) when children prepared to direct attention to the spatial location or gender of an upcoming target talker who spoke in a mixture of three talkers. Compared to normally-hearing children, hearing-impaired children showed significantly less evidence of preparatory brain activity when required to direct spatial attention. This finding is consistent with the idea that hearing-impaired children have a reduced ability to prepare spatial attention for an upcoming talker. Moreover, preparatory brain activity was not restored when hearing-impaired children listened with their acoustic hearing aids. An implication of these findings is that steps to improve auditory attention alongside acoustic hearing aids may be required to improve the ability of hearing-impaired children to understand speech in the presence of competing talkers.

Key words

Hearing loss; Multi-talker listening; Auditory Attention; Spatial attention; EEG; CNV

1. Introduction

Listeners with normal hearing can deploy attention successfully and flexibly to a talker of interest when multiple talkers speak at the same time (Larson and Lee, 2014; O'Sullivan et al., 2014), an ability that is fundamental to successful verbal communication. These multi-talker (or "Cocktail Party") listening environments are particularly challenging for people with hearing loss, as demonstrated both by accuracy scores and self-report (Dubno et al., 1984; Helfer and Freyman, 2008). As a result of this difficulty, children with hearing loss may be at a particular disadvantage when learning language, because they not only have to do so with distorted representations of the acoustic features of speech, but also frequently hear speech in acoustic environments with multiple competing talkers. At least part of the difficulty in multi-talker listening arises from impairments in peripheral transduction in the ear, including loss of sensitivity to higher frequencies (Hogan and Turner, 1998), impaired frequency selectivity (Gaudrain et al., 2007; Moore, 1998), and impaired ability to interpret temporal fine structure (Lorenzi et al., 2006). However, it is currently unclear to what extent atypical cognitive abilities contribute to the difficulties in multi-talker listening experienced by children with moderate hearing loss (who experience distortions in peripheral processing, although retain residual hearing). The current experiments compared the ability of hearing-impaired and normally-hearing children to direct preparatory attention to the spatial location or gender of a talker during multi-talker listening.

Cognitive abilities have been found to differ between children with normal hearing and children who use cochlear implants (CIs). Children with severe-to-profound loss who use CIs score more poorly on tests of working memory and inhibitory control than normally-hearing children (Beer et al., 2014, 2011). This finding demonstrates that atypical auditory input can potentially affect the development of cognitive abilities. However, the extent to which preserved auditory encoding matters for executive function is currently unclear. Given that children with CIs have minimal residual hearing and may have undergone a period of auditory deprivation in childhood prior to implantation, it is unclear whether adults who acquired hearing loss later in life or people with less severe hearing losses would also exhibit atypical executive functions.

As a result of the inherent difficulty of separating peripheral from cognitive processes, it remains unclear whether moderate hearing loss has downstream consequences for cognitive auditory abilities. Neher *et al.* (2009) used the Test of Everyday Attention (Robertson et al., 1996) to measure attention and working memory in adults with moderate hearing loss. Speech reception thresholds in hearing-impaired adults during multi-talker listening were correlated with selective attention, attentional switching, and working memory. However, most of the participants were older adults (mean age of 60 years) and speech reception thresholds were significantly correlated with age; thus, it is possible that declines in cognitive and peripheral auditory processing are unrelated to each other, but both related independently to aging (for example, as a result of decreased cortical volume in older people; e.g. Cardin, 2016).

Instead of using behavioural tests to investigate cognitive function, several studies have measured cortical responses in listeners with moderate hearing loss. For example, Peelle *et al.* (2011) found that average pure-tone hearing thresholds predicted the extent to which spoken sentences evoked activity in the bilateral superior temporal gyri, thalamus, and brainstem in hearing-impaired adults. Several studies using electro-encephalography (EEG) and magneto-encephalography (MEG) have also shown atypical auditory evoked activity in hearing-impaired adults (Alain et al., 2014; Campbell and Sharma, 2013; Oates et al., 2002) and children (Koravand et al., 2012). However, although these studies measured cortical activity, they do not necessarily indicate atypical cognitive processes in hearing-impaired listeners: differences in neural activity between normally-hearing and hearing-impaired listeners could arise *either* due to impaired cognitive function or because normal cognitive processes are deployed onto a distorted central representation of the acoustic signal. The current experiment avoided this confound by seeking evidence of differences in neural activity when participants prepared to direct attention to speech (i.e. before the speech began) during multi-talker listening.

Normally-hearing listeners can use between-talker differences in acoustic properties as cues to improve the intelligibility of speech spoken by a target talker during multi-talker listening. For example, normally-hearing listeners show better speech intelligibility when the talkers differ in gender (Brungart, 2001; Brungart et al., 2001; Shafiro and Gygi, 2007), fundamental frequency (Assmann and Summerfield, 1994; Darwin and Hukin, 2000), or spatial location (Bronkhorst and Plomp, 1988; Darwin and Hukin, 1999; Helfer and Freyman, 2005). Normally-hearing listeners can also deploy preparatory attention to these acoustic cues before a target talker starts to speak. First, they achieve better accuracy of speech intelligibility when they know the spatial location (Best et al., 2009, 2007; Ericson et al., 2004; Kidd et al., 2005) or the identity (Freyman et al., 2004; Kitterick et al., 2010) of a target talker before he or she begins to speak. Second, previous experiments using functional magnetic resonance imaging (fMRI; Hill and Miller, 2010) and MEG (Lee et al., 2013) have revealed preparatory brain activity that differs depending on whether normally-hearing adults direct attention to the spatial location or fundamental frequency of the target talker. Normally-hearing adults and children also show preparatory EEG activity when they are cued to the location or gender of a target talker (Holmes et al., 2016). If hearing-impaired children deploy preparatory attention in a similar way as normally-hearing children do, there should be no differences in preparatory EEG activity between normally-hearing and hearing-impaired children.

In the current experiment, we presented an adult male and an adult female voice concurrently from different spatial locations. A third, child's, voice was also presented to increase the difficulty of the task. Prior to the presentation of the voices, a visual stimulus cued attention to either the spatial location or gender of the target talker, who was always one of the two adults. The task was to report key words spoken by the target talker. We recorded brain activity using electro-encephalography (EEG) in children with moderate sensorineural hearing loss of several year's duration (HI children) and in a comparison group of normally-hearing (NH) children. We isolated preparatory EEG activity by comparing event-related potentials (ERPs) between a condition in which the visual cue indicated the location or gender of an upcoming target talker and a control condition in which the same visual cues were presented but did not instruct participants to attend to acoustic stimuli. We hypothesised that we would find less evidence of preparatory EEG activity in hearing-impaired children than in normally-hearing children.

2. Methods

2.1. Participants

Participants were 24 children with normal hearing (9 male), aged 8–15 years (mean [M] = 12.3, standard deviation [SD] = 1.9) and 14 children with sensorineural hearing loss (4 male), aged 7–16 years (M = 11.6, SD = 3.1). All participants were declared by their parents to be native English speakers. The NH children were all also declared by their parents to be right-handed with no history of hearing problems and they had 5-frequency average pure-tone hearing levels of 15 dB HL or better, tested in accordance with BS EN ISO 8253-1 (British Society of Audiology, 2004; Fig. 1). The children with hearing loss had bilateral 5-frequency average pure-tone hearing levels between 42 and 65 dB HL (M = 50.4 dB HL, SD = 7.9; Fig. 1) and the difference in the 5-frequency averages recorded from the left and right ears was less than 12 dB for each participant. Of the fourteen HI children, two were left-handed and one had an additional visual impairment in her left eye. The study was approved by the Research Ethics Committee of the Department of Psychology, University of York, the NHS Research Ethics Committee of Newcastle and North Tyneside, and the Research and Development Departments of York Teaching Hospital NHS Foundation Trust, Leeds Teaching Hospitals NHS Trust, Hull and East Yorkshire Hospitals NHS Trust, and Bradford Teaching Hospitals NHS Foundation Trust.

< Insert Fig. 1 >

The HI children completed the experiment for the first time without using their hearing aids. A subset of ten HI children (aged 7–16 years, M = 11.9 years, SD = 2.5; 2 male; 1 left-handed) also took part in the experiment for a second time using their own acoustic bilateral behind-the-ear hearing aids. The aided session took place between 2 and 9 months after the unaided session. We refer to the entire group who participated in the unaided session as the HI_U group. For the children who took part in both aided and unaided sessions, we distinguish between HI_A and HI_U sessions, respectively.

2.2. Materials

The experiment was conducted in a 5.3 m x 3.7 m single-walled test room (Industrial Acoustics Co., NY) located within a larger sound-treated room. Participants sat facing three loudspeakers (Plus XS.2, Canton) arranged in a circular arc at a height of 1 m at 0° azimuth (fixation) and at 30° to the left and right (Fig. 2A). A 15-inch visual display unit (VDU; NEC AccuSync 52VM) was positioned directly below the central loudspeaker.

Four visual cues, “left”, “right”, “male”, and “female”, were defined by white lines on a black background. Left and right cues were leftward- and rightward-pointing arrows, respectively; male and female cues were stick figures (Fig. 2B–E). A composite visual stimulus consisted of the four cues overlaid (Fig. 2F).

< Insert Fig. 2 >

Acoustical test stimuli were modified phrases from the Co-ordinate Response Measure corpus (CRM; Moore, 1981) spoken by native British English talkers (Kitterick et al., 2010). One male and one female talker were selected from the corpus. An additional female talker was selected from the corpus, whose voice was manipulated to sound like a child’s voice by simulating a change in F0 and vocal tract length using Praat (Version 5.3.08; http://www.praat.org/). The original stimuli were edited so that each phrase had the form ‘<colour> <number> now’. There were four colours (‘Blue’, ‘Red’, ‘Green’, ‘White’) and four numbers (‘One’, ‘Two’, ‘Three’, ‘Four’). An example is “Green Two now”. The average duration of the presented phrases was 1.4 s. The levels of the digital recordings of the phrases were normalised to the same root mean square (RMS) power.

Control stimuli were single-channel noise-vocoded representations of concurrent triplets of modified CRM phrases that were used as acoustical test stimuli. Each control stimulus was created by summing three acoustical test phrases (one spoken by each talker) digitally with their onsets aligned and extracting the temporal envelope of the combination using the Hilbert Transform (Hilbert, 1912). We used the envelope to modulate the amplitude of a random noise whose long-term spectrum matched the average spectrum of all of the possible triplets of phrases.

2.3. Procedures

Fig. 3A illustrates the trial structure in the test condition. The visual cue directed attention to the target talker and varied quasi-randomly from trial to trial. The cue remained on the screen throughout the duration of the acoustic stimuli so that participants did not have to retain the visual cue in memory. The three different talkers were presented from the three loudspeakers (left, middle, and right). The phrases started simultaneously, but contained different colour-number combinations. The ‘child’ talker was always presented from the middle loudspeaker and was always unattended. Over the course of the experiment, the male and female talkers were presented equally often from the left and right locations. After the phrases had ended, participants were instructed to report the colour-number combination in the target phrase by pressing a coloured digit on a touch screen directly in front of their chair. Each participant completed between 96 and 144 trials in the test condition (depending on their stamina), with an equal number of each the four cue types. There was a short break every 16 trials and longer break every 48 trials.

< Insert Fig. 3 >

The average presentation level of concurrent pairs of test phrases was set to 63 dB(A) SPL (range 61.6—66.2 dB) for normally-hearing children and 76 dB(A) SPL (range 72.4—77.9 dB) for hearing-impaired children. This difference aimed to compensate, in part, for higher pure-tone thresholds of the hearing-impaired children. Presentation levels were measured with a B&K (Brüel &

Kjær, Nærum, Denmark) Sound Level Meter (Type 2260 Investigator) and 0.5-inch Free-field Microphone (Type 4189) placed in the centre of the arc at the height of the loudspeakers with the participant absent.

The trial structure in the control condition was the same as in the test condition (Fig. 3B) with the exception that an acoustical control stimulus, presented from the loudspeaker at 0° azimuth, replaced the triplet of acoustical test stimuli. The purpose of the control condition was to measure responses to the visual cues when they had no implications for auditory attention. The task was to identify the picture that corresponded to the visual cue on each trial. The logic behind the design of the control condition was that the acoustic stimuli lacked the spectral detail and temporal fine structure required for the perception of pitch (Moore, 2008). In addition, because the stimuli were presented from one loudspeaker, they did not provide the interaural differences in level and timing required for their constituent voices to be localised separately. In these ways, the acoustic cues required to segregate the sentences by gender and by location were neutralised, while the overall energy and gross fluctuations in amplitude of the test stimuli were preserved. Each participant completed 96 trials (24 in each cue type condition) with a short break every 12 trials and a longer break every 36 trials. The presentation level of the acoustical control stimuli was set so that their average level matched the average level of the triplets of test stimuli. Participants undertook the control condition before the test condition; that is, before they had learnt the association between the visual cues and the acoustical test stimuli.

After participants had completed the control condition, but before they undertook the test condition, they completed two sets of familiarisation trials, which had a similar trial structure to the test condition. In the first set (12 trials), *either* the male or female talker was presented on each trial from the left or right loudspeaker. In the second set (4 trials), each trial contained all three voices, identical to the test condition. EEG activity was not recorded during familiarisation.

2.4. Behavioural analyses

Trials were separated into location (average left/right cues) and gender (average male/female cues) groups, separately for the test and control conditions. Responses were scored as correct if both the colour and number key words were reported correctly in the test condition and if the visual cue was reported correctly in the control condition. A 2 x 2 between-subjects ANOVA compared accuracy between NH and HI_U children for the location and gender cue types. A 2 x 2 within-subjects ANOVA contrasted the subset of HI children who completed both the aided and unaided sessions (HI_A and HI_U).

2.5. EEG recording and processing

Continuous EEG was recorded using the ANT WaveGuard-64 system (ANT, Netherlands; www.ant-neuro.com) with Ag/AgCl electrodes (with active shielding) mounted on an elasticated cap (positions: Fp1, Fp2, AF3, AF4, AF7, AF8, F1, F2, F3, F4, F5, F6, F7, F8, FC1, FC2, FC3, FC4, FC5, FC6, FT7, FT8, C1, C2, C3, C4, C5, C6, T7, T8, CP1, CP2, CP3, CP4, CP5, CP6, TP7, TP8, P1, P2, P3, P4, P5, P6, P7, P8, PO3, PO4, PO7, PO8, O1, O2, M1, M2, Fpz, Fz, FCz, Cz, CPz, Pz, POz, Oz). An additional electrode (AFz) was used as a ground site. The horizontal electro-oculogram (EOG) was measured with a bipolar lead attached to the outer canthi of the left and right eyes and the vertical EOG was measured with a bipolar lead above and below the right eye. The EEG was amplified and digitised with an ANT High-Speed Amplifier at a sampling rate of 1000 Hz per channel. Electrode impedances at the start of the experiment were below 30 kOhm.

The continuous EEG recordings were exported to MATLAB 7 (The MathWorks, Inc., Natick, MA, USA). The data was processed using the EEGLAB toolbox (Version 9; http://sccn.ucsd.edu/eeglab/) and ERPs were statistically analysed using the FieldTrip toolbox (http://fieldtrip.fcdonders.nl/). Before statistical analysis, the data were band-pass filtered between 0.25 and 30 Hz. The purpose of bandpass filtering was to remove DC offset, slow drifts due to skin potentials, line noise, and muscle-related artefacts. The amplitude at each electrode was referenced to the average amplitude of the electrode array. Epochs were created with 4700 ms duration, including a baseline interval of 200 ms at the end of the fixation-cross period. Given that HI children performed the task with low accuracy, we included correct and incorrect trials in the analyses to improve power for detecting differences between NH and HI children. However, including incorrect trials in the analysis did not lead to qualitatively different ERPs, or different conclusions from statistical tests, than when incorrect trials were excluded (see Supplementary Fig. 2). Independent component analysis (ICA) was used to correct for eye-blink artifacts, which were identified by a stereotyped scalp topography. There were no discernible artefacts attributable to the hearing aids in the pre-processed data from the $\mathrm{HI_A}$ session.

2.6. Analyses of ERPs

Fig. 4 shows a schematic of the EEG analysis pipeline. We used cluster-based permutation analyses (Maris and Oostenveld, 2007) to identify differences in EEG activity between the test and control conditions (separately for location and gender trials) and between location and gender trials (within the test condition). The method searches for clusters of adjacent electrodes over successive time points that display systematic differences between two experimental conditions. The value of the *t*-statistic is calculated for each electrode at each time point. Clusters are then tested for significance by comparing the sum of the *t*-values within the observed cluster against the null distribution, which is constructed by permuting the data between conditions and searching for clusters in the permuted data. We used this method first to identify preparatory attention in NH children and, second, in $\mathrm{HI_U}$ children; we conducted the cluster-based permutation analysis in the interval between the full reveal of the visual cue and the onset of acoustic stimuli (duration = 2000 ms).

< Insert Fig. 4 >

For each significant cluster identified in the NH children, the magnitude of the cluster—calculated as the difference in amplitude between conditions, averaged across the electrodes and time points that contributed to the cluster—was compared between NH and $\mathrm{HI_u}$ children using bootstrapping. First, a sample of 14 children was selected (with replacement) from the NH group;

100,000 samples were selected to form a null distribution. Second, the average magnitude of each cluster for the 14 HI_U children was compared against the null distribution in a two-tailed test (α = 0.95). The purpose of this analysis was to equate the group sizes for NH and HI_U children. The same comparison was conducted between the 10 HI_A children and samples of 10 NH children.

To compare ERPs for the hearing-impaired children when they listened aided and unaided, a within-subjects *t*-test compared the average magnitude of each cluster in the sub-set of children who completed both the aided and unaided sessions.

3. Results

3.1. Behavioural results

NH children achieved significantly higher accuracy of speech intelligibility (M = 66.3%, SD = 15.4) than HI_U children [M = 29.0%, SD = 15.4; $F(1, 36) = 51.71$, $p < 0.001$, $\eta_p^2 = 0.59$; Fig. 5], with no significant difference between trials in which they were cued to location (left/right) and gender (male/female) [$F(1, 36) = 3.82$, $p = 0.06$] and no significant interaction between hearing group and cue type [$F(1, 36) = 0.95$, $p = 0.34$]. In the control condition, there was no significant difference in accuracy for identifying the visual cues between NH (M = 98.1%, SD = 3.9) and HI_u children [M = 94.7%, SD = 4.4; $F(1, 36) = 1.43$, $p = 0.24$]. There was also no significant difference between cue types [$F(1, 36) = 3.14$, $p = 0.09$] and no significant interaction [$F(1, 36) = 1.43$, $p = 0.24$].

HI children identified words spoken by the target talker with significantly higher accuracy in the aided (M = 41.3%, SD = 20.4) than the unaided (M = 28.5%, SD = 20.3) session [$F(1, 9) = 25.71$, $p = 0.001$, $\eta_p^2 = 0.74$]. There was no significant difference between cue types [$F(1, 9) = 0.60$, $p = 0.46$] and no significant interaction [$F(1, 9) = 0.92$, $p = 0.36$]. In the control condition, there was no significant difference in accuracy for identifying the visual cues between the aided (M = 93.4%, SD = 10.4) and unaided (M = 94.4%, SD = 9.2) sessions [$F(1, 9) = 0.38$, $p = 0.27$] and no significant difference between cue types [$F(1, 9) = 0.16$, $p = 0.70$]. There was a marginal significant interaction between aiding and cue type in the control condition [$F(1, 9) = 5.44$, $p = 0.045$, $\eta_p^2 = 0.38$]†.

< Insert Fig. 5 >

3.2. Event-related potentials: Evidence for preparatory attention

First, using cluster-based permutation analyses, we sought evidence of preparatory attention in NH children. Fig. 6 illustrates the topography and time windows of clusters that showed significant differences between the test and control conditions. Additional information about each cluster is tabulated in Table 1. Analyses were conducted separately for trials in which participants were cued to location (left/right) and gender (male/female).

< Insert Fig. 6 >

< Insert Table 1 >

Three significant clusters of activity were found for location trials (Clusters 1–2) and one significant cluster was found for gender trials (Cluster 3N). The emergence of these significant clusters is compatible with the idea that NH children prepare attention for the location and gender of an upcoming talker.

3.3. Event-related potentials: Comparisons between location and gender trials

To establish whether NH children showed differences in brain activity depending on the attribute of the target talker to which they were attending, we compared ERPs between location and

†This interaction reflected average accuracy on location trials that was slightly, but not significantly, higher than on gender trials in the aided session ($p = 0.40$), but average accuracy that was slightly, but not significantly, higher on gender than on location trials in the unaided session ($p = 0.87$).

gender trials within the test condition. No significant clusters were found. Thus, further analyses focussed on examining the clusters that showed significantly different activity between the test and control conditions.

3.4. Event-related potentials: Differences between NH and HI children

Bootstrapping analyses compared the magnitude of each cluster between NH children and HI children. Cluster magnitude was defined as the difference in amplitude between conditions, averaged across the electrodes and time points that contributed to the cluster.

Fig. 7 illustrates the average cluster magnitude for NH and HI_U children. For location trials, the magnitude of all three clusters were significantly different for HI_U than NH children (i.e. HI_U children either showed a significantly smaller difference in amplitude between the test and control conditions than NH children or a difference in the opposite direction to NH children) [Cluster 1N: $p = 0.002$; Cluster 2N: $p < 0.001$; Cluster 2P: $p < 0.001$; Table 1].

< Insert Fig. 7 >

Comparisons between HI_A and NH children for location trials showed the same pattern of results, except that the earliest cluster did not differ significantly between HI_A and NH children [Cluster 1N: $p = 0.14$; Cluster 2N: $p = 0.001$; Cluster 2P: $p = 0.002$; Table 1].

For gender trials, cluster magnitude did not differ significantly between NH and HI_u children (Cluster 3N: $p = 0.13$), although it did differ between NH and HI_A children (Cluster 3N: $p = 0.009$).

Overall, converging results from the aided and unaided sessions show a difference in preparatory EEG activity between HI and NH children during location trials (Clusters 2N and 2P) but no consistent evidence for a difference during gender trials. This result demonstrates the key finding that HI children prepare spatial attention to a lesser extent than NH children.

Additional information about each cluster is tabulated in Table 1. The ERP waveforms at each cluster are illustrated in Supplementary Fig. 1.

3.5. Event-related potentials: Comparisons between aided and unaided conditions

In order to test whether aiding affected the *extent* of preparatory attention in HI children, the magnitude of the clusters was compared between the HI_U and HI_A sessions. A paired-samples *t*-test was conducted on the data from the 10 participants who completed both sessions. None of the clusters showed significant differences between the aided and unaided sessions [Cluster 1N: $t(9) = 0.11$, $p = 0.92$; Cluster 2N: $t(9) = 1.23$, $p = 0.25$; Cluster 2P: $t(9) = 2.13$, $p = 0.06$; Cluster 3N: $t(9) = 1.21$, $p = 0.26$]. These results suggest that different significance patterns for the comparisons of Cluster 1N and 3N between NH and HI_U groups and between NH and HI_A groups (Section 3.4) do not reflect significant differences between aided and unaided listening. The results demonstrate that aiding did not affect magnitude of the clusters; thus, there was no greater evidence of preparatory attention in HI children when they used their hearing aids than when they listened unaided.

3.6. Event-related potentials: Clusters in HI children

To investigate whether HI and NH children showed qualitatively different patterns of brain activity, we also conducted spatio-temporal cluster-based permutation analyses on the data from the HI_U children, without limiting the analyses to specific groups of electrodes or time points. In other words, these further analyses aimed to determine whether the group of HI children showed consistent evidence of preparatory attention (indicated by the presence of a significant spatio-temporal cluster) that differed in magnitude from activity in NH children.

We found no significant clusters for location trials (Fig. 8A). One significant cluster was found for gender trials, which occurred soon after the visual cue was revealed (Cluster 4N; Fig. 8B–C; Table 1). We compared the magnitude of this cluster between NH and HI_U children in a bootstrapping analysis, using the method described in Section 3.4. There was no significant difference in the magnitude of Cluster 4N between NH (M = -0.28 µV) and HI_U (M = -0.57 µV) children ($p = 0.08$; Fig. 8D), suggesting that HI children did not evoke qualitatively different EEG activity to NH children.

< Insert Fig. 8 >

3.7. Event-related potentials: Variability in NH and HI children

Given our sample of HI children varied in both age and aetiology, it was possible that the HI children were more variable in evoking preparatory EEG activity than NH children. We used Levene's test for equality of variances to determine whether the variance in cluster magnitude differed between the NH and HI_U children. There were no significant differences in variance for any of the four clusters found in NH children [Cluster 1N: $F = 0.70$, $p = 0.41$; Cluster 2N: $F = 27$, $p = 0.61$; Cluster 2P: $F = 0.26$, $p = 0.61$; Cluster 3N: $F = 2.67$, $p = 0.11$]. This result demonstrates that HI children were no more variable than NH children in evoking preparatory EEG activity. Thus, increased variability was not the reason why we found fewer significant clusters in HI children than NH children.

4. Discussion

HI children showed significantly less evidence of preparatory attention than NH children, demonstrated by smaller differences in event-related potentials (ERPs) when visual stimuli cued spatial attention to one of three talkers compared to when the same visual stimuli had no implications for auditory attention. Such differences would arise if hearing-impaired children deployed less preparatory activity than normally-hearing children, or if they invoked activity with different latencies or in different brain regions that varied across the group of hearing-impaired children. Thus, the result is compatible with the idea that HI children prepare spatial attention less consistently than NH children.

4.1. Preparatory EEG activity in NH children

Previous experiments demonstrate that adults and children aged 7–13 years with normal hearing show preparatory brain activity before a target talker begins to speak (Hill and Miller, 2010; Holmes et al., 2016; Lee et al., 2013). Consistent with this finding, NH children aged 8–15 years in the current experiment showed significant differences in ERPs between trials in which a visual cue directed attention to the spatial location of an upcoming talker and trials in which the same visual cue was presented but did not have implications for auditory attention. The current results are consistent with the idea that NH children prepare their attention for the location of an upcoming target talker during multi-talker listening.

Preparation for location evoked significant activity in two distinct time periods: the first started shortly (< 75 ms) after the visual cue was revealed and lasted for approximately 300 ms; the second occurred throughout the 1000 ms immediately before the talkers began to speak. In general, these findings are consistent with the idea that participants with normal hearing evoke preparatory brain activity before the onset of an acoustical target stimulus (Banerjee et al., 2011; Müller and Weisz, 2012; Voisin et al., 2006). These findings are also consistent with the results of previous experiments with a similar design that tested adults and children with normal hearing (Holmes et al., 2016). Holmes *et al.* (2016) used a speech intelligibility task that was similar to the current experiment, except that (1) two, rather than three, talkers spoke simultaneously and (2) the preparatory interval was 1000 ms instead of 2000 ms. Similar to the current experiment, Holmes *et al.* (2016) found preparatory activity that began soon after a visual cue for location was presented and which was sustained before two talkers started speaking. However, by using a longer preparatory interval, the current experiment separated preparatory activity that occurred in two distinct time periods: the first occurred shortly after the visual cue was revealed and thus likely reflects initial processing and interpretation of the cue; the second occurred immediately before the talkers begin speaking and may therefore reflect anticipation of characteristics of the upcoming talkers.

The preparatory ERPs identified in NH children that occurred in the 1000 ms immediately before the talkers began to speak resemble the contingent negative variation (CNV; Walter et al., 1964), an ERP thought to reflect anticipation of an upcoming stimulus (e.g. Chennu et al., 2013). Figures 6C (location trials) and 6F (gender trials) show that ERPs in the test condition were significantly more negative than the control condition immediately before the talkers started speaking (1170–0 ms prior to the onset of the talkers in location trials and 473–0 ms prior in gender trials); during these time periods, ERPs elicited by visual cues in the control condition (in which acoustic stimuli were presented but were not relevant to the participants' task) were approximately at baseline level, whereas ERPs in the test condition were negative. Thus, differences in ERPs between the test and control conditions in Figures 6C and 6F might possibly reflect the CNV (although it is unclear whether the topography observed in the current experiment matches that of the CNV, given that the current experiment used the average reference and previous CNV experiments have typically used a mastoids or tip of the nose reference).

The latency of the CNV is correlated with the length of subjective judgements of interval duration (Ruchkin et al., 1977), suggesting that the CNV reflects anticipation of the time at which a target stimulus will occur. In addition, the CNV has been observed in both the visual and auditory modalities (e.g. Pasinski et al., 2016; Walter et al., 1964), which suggests it reflects preparation that is not specific to any particular attribute or modality. Indeed, consistent with the idea that the CNV does not only reflect preparation for one particular stimulus attribute, we observed activity resembling the CNV on both location (Figure 6C) and gender (Figure 6F) trials and found no significant differences in preparatory ERPs between location and gender trials. Given that larger CNV magnitudes are related to better detection of acoustic target stimuli (Rockstroh et al., 1993), the activity shown in Figures 6C and 6F may reflect preparatory activity that is beneficial for speech intelligibility during multi-talker listening.

4.2. Differences between NH and HI children

Comparisons between NH and HI children showed atypical ERPs in HI children during location trials—the difference in amplitude between the test and control conditions was significantly smaller for HI than NH children (Clusters 2N and 2P; Fig. 7A). Moreover, that result was found when HI children listened both unaided and aided. This result is consistent with the idea that HI children do not deploy preparatory spatial attention to the same extent as NH children. Compatible with this finding, HI children also showed significantly poorer accuracy of speech intelligibility than NH children. Since directing preparatory spatial attention has previously been found to improve the understanding of a talker by adults with normal hearing (Best et al., 2007; Ericson et al., 2004; Kidd et al., 2005), it is possible that difficulties preparing spatial attention contributed to poor speech understanding by HI children during the current task. The idea that HI children do not engage preparatory brain activity to the same extent as NH children is consistent with the results of Best *et al.* (2009) who showed that adults with moderate hearing loss gained less improvement in the accuracy of speech intelligibility than NH adults when they were cued to the spatial location of a talker. Together, the findings of Best *et al.* and the current experiment suggest that hearing loss leads to atypical preparatory attention, which reduces the benefit to speech understanding gained from knowing the spatial location of a talker before they start speaking.

One difference between HI and NH children was in the cluster that resembled the CNV (Cluster 2N, Figure 7A). There is some evidence from magnetoencephalography (MEG; Basile et al., 1997) and EEG (Segalowitz and Davies, 2004) source localisation that the magnitude of the CNV is related to the magnitude of activity in prefrontal cortex. Segalowitz and Davis (2004) showed that the development of executive functions, such as working memory, in children relates to the strength of the CNV in a Go/No-Go task and they, thus, suggest that the CNV may relate to development of the frontal attentional network. Consistent with this idea, lower CNV magnitudes are observed in reaction-time tasks when distracting visual stimuli that need to later be recalled are presented in the interval between a cue and an auditory target stimulus than when no distracting stimuli are presented (Tecce and Scheff, 1969; Travis and Tecce, 1998). Thus, it is possible that the difference in Cluster 2N between HI and NH children could result from HI children having a less mature frontal attentional network. On the other hand, Wöstmann *et al.* (2015) showed that, within participants, the magnitude of the CNV related to task difficulty and to the extent of temporal fine structure degradation of acoustic speech stimuli. Therefore, the difference in Cluster 2N in the current experiment could reflect greater difficulty of multi-talker listening for HI children, a loss of temporal fine structure information resulting from hearing loss, or a combination of both of these factors. Future experiments could distinguish these possibilities by examining the extent to which the difference in preparatory ERPs exists between NH and HI children under different task conditions. For example, preparatory brain activity could be compared between NH and HI children during multi-talker listening when the speech stimuli are degraded for both groups and when the accuracy of speech intelligibility is similar for NH and HI children. Any differences in preparatory brain activity could attempt to be localised using EEG or MEG source reconstruction techniques to examine whether differences could be attributable to development of the frontal attention network.

The current results demonstrate atypical spatial auditory attention in children with moderate hearing loss, although the typical role of experience on the development of this ability is unclear. One hypothesis is that a degraded representation of the cues used to distinguish talkers by their location results in a reduced ability to prepare to attend to a talker based on his or her spatial location. This hypothesis is consistent with the idea that reduced preparatory spatial attention is a direct consequence of hearing loss and predicts that atypical spatial attention would be observed in all listeners whose hearing loss distorts the ability to resolve sounds at different spatial locations. In addition, this hypothesis suggests that preparatory spatial attention could be restored only if the peripheral representation of spatial location is also restored. Alternatively, hearing loss may affect the ability to direct selective attention in a more general manner that is not specific to the peripheral cues to which the listener has access. The latter hypothesis seems more likely, given that hearing-impaired children in the current experiment were able to perform the task with above-chance accuracy despite showing no consistent evidence of preparatory attention. This result suggests that the children had sufficient peripheral representations of spatial location to identify a target talker based on their location. However, further work is required to disambiguate these two alternatives. For example, future experiments could investigate the relationship between spatial localisation and/or discrimination abilities and preparatory attention in hearing-impaired people.

During gender trials, there was no consistent evidence for atypical ERPs in HI children, although, NH children did not display preparatory attention for gender to the same extent as they displayed preparatory attention for location (Fig. 7). It is possible that the cues for gender used in the current experiment evoked preparatory attention only minimally for both NH and HI children. This interpretation is consistent with the results of Holmes *et al.* (2016) who also found minimal evidence of preparatory EEG activity when NH children were cued to the gender of a target talker.

The analyses reported in this paper included correct and incorrect trials. The rationale was that HI children performed the task with low accuracy and, therefore, removing all incorrect trials would lead to lower signal-to-noise ratio in the average ERPs and, hence, lower statistical power to detect differences between NH and HI children. However, this decision meant that differences in EEG activity between NH and HI children could potentially reflect differences in behavioural performance between NH and HI children, rather than the EEG activity that accompanied successful trials (which might produce confounds, for example, if one group was not engaged in the task for all trials of the experiment). We, thus, conducted a separate analysis in HI children comparing activity evoked on correct trials with average activity evoked on correct and incorrect trials. The analysis of correct trials revealed similar patterns of activity as the analysis that included correct and incorrect trials. This result suggests that differences between NH and HI children cannot be explained by the contribution of qualitatively different activity on incorrect than correct trials. Instead, the results are attributable to differences in preparatory EEG activity between the NH and HI groups.

4.3. Effect of aiding

A within-subjects comparison between the aided and unaided sessions (which were conducted on different days, separated by up to nine months) showed no significant difference in the magnitude of the clusters. In addition, comparisons between NH and HI_A groups showed similar results to comparisons between NH and HI_U children—in both instances, Clusters 2N and 2P (which occurred on location trials) showed significant differences between the NH and HI children. This result demonstrates that differences in preparatory attention between HI and NH children did not arise due to unfamiliar listening conditions or lack of audibility in the HI children. Another implication of this result is that acoustic hearing aids do not restore normal preparatory spatial attention in children with moderate sensorineural hearing loss.

4.4. Possible compensatory mechanisms

The results demonstrate that HI children do not display the same preparatory processes as NH children when they are cued to the location of an upcoming talker. Furthermore, we found no consistent evidence of preparatory spatial attention in HI children because there were no significant clusters in HI children during location trials (Fig. 8A). This outcome is consistent with the idea that HI children did not systematically compensate for hearing loss by engaging qualitatively different preparatory brain activity to NH children or by engaging similar brain activity with a different time course. Rather, the results are consistent with the idea that the group of HI children, overall, showed either weaker or less consistent preparatory spatial attention than the group of NH children.

There was one significant cluster in HI children during gender trials, which occurred very soon after the visual cue was revealed (Fig. 8B–C). However, there was no evidence that the magnitude of this cluster differed between NH and HI_U children, which is again consistent with idea that HI children did not engage qualitatively different preparatory brain activity to NH children.

Although HI children did not show additional preparatory activity that was different to the NH children, different hearing-impaired children might have adopted different strategies to prepare attention. The resulting lack of consistency might explain the general absence of significant clusters in the group of HI children. We do not have information about the specific aetiology, duration of hearing loss, or time of onset of the hearing loss for the HI children, but variability in these factors could potentially be related to differences in preparatory attention. On the other hand, if those factors had a large impact on preparatory EEG activity, we would expect individual variability in HI children to be greater than that in NH children. The data do not provide evidence to support this idea, given that the variance in cluster magnitude did not differ significantly between HI_U and NH children. Although the current numbers of participants do not provide sufficient power to examine whether preparatory EEG activity related to age or audiometric thresholds, characterising the factors that influence the extent of preparatory attention in children with normal and impaired hearing would be an interesting aim for future studies.

The children who took part in the current experiment may have undergone a period of auditory deprivation resulting from their hearing loss during a critical or sensitive period of development. If this explanation is correct, individuals who acquired hearing loss during adulthood may not show similar deficits in preparatory attention. Furthermore, preparatory attention would be expected to differ between different people with hearing loss, depending on the age of onset of their hearing loss and perhaps also on the age at which they received hearing aids.

In addition, the current experiment tested individuals with moderate hearing loss and, thus, it is not clear whether the extent of hearing loss affects the extent to which attention is atypical. Beer *et al.* (2011, 2014) measured executive functions in children with severe-to-profound hearing loss who used CIs. Compared to normally-hearing children, children with CIs showed reduced ability to perform tests of working memory and inhibitory control. This result is consistent with the idea that hearing loss has consequences for central processing. This result is also relevant to the current findings because preparing to attend to a talker may be related to the processes of maintaining in memory the identity and spatial locations of multiple talkers and inhibiting the representations of irrelevant talkers. The experiments of Beer and colleagues differ from the current experiments in that they used parent reports of executive function abilities (Beer et al., 2011) and visual tests of executive function (Beer et al., 2014). Therefore, a comparison between the current experiment and the experiments of Beer and colleagues does not reveal whether the types or extent of executive function deficits differ between children with moderate and children with severe-to-profound hearing loss.

Children with severe-to-profound hearing loss might be expected to show greater deficits in executive function abilities, or perhaps a wider variety of executive function abilities that are affected, than children with moderate hearing loss. That prediction follows from the idea that children with severe-to-profound hearing loss would have experienced a period of time (between the onset of hearing loss and receiving cochlear implants) during which they were more deprived of acoustic stimulation than children with moderate hearing losses (who would have experienced a delay between the onset of hearing loss and receiving hearing aids, but who have greater preservation of residual hearing). In addition, CIs and hearing aids provide different types of acoustic information to the listener that may affect the ability of executive functions to develop after rehabilitation. The current experiment reveals that children with moderate hearing loss show atypical preparatory attention during multi-talker listening, which might relate directly to the difficulty they experience in multi-talker environments; however, it does not reveal whether other executive functions, including those in other sensory modalities, are atypical. Nevertheless, a link between the lack of preparatory activity obtained in the current experiment and broader executive function abilities is possible because the development of executive functions, such as working memory, has been related to the strength of the CNV (Segalowitz and Davies, 2004). Greater understanding of how hearing loss affects executive function could be gained by directly comparing individuals with different hearing loss aetiologies on the same executive function tasks. In addition, it would be informative for future studies to examine the relationship between preparatory attention during multi-talker listening and a broader range of executive function abilities.

4.5. Implications

Current interventions for impaired hearing, such as acoustic hearing aids, are targeted at overcoming a loss of sensitivity at the auditory periphery. The current results have potential implications for rehabilitation, because they suggest that atypical auditory attention might be one factor that contributes to difficulty understanding speech for HI children during multi-talker listening. Although it is currently unclear how attention abilities could be restored, improving auditory attention abilities (e.g. through training) might help hearing-impaired children to understand speech in the presence of other competing speech—a situation that would frequently be encountered in noisy environments at home and at school.

Better understanding of the conditions under which hearing loss affects attention and the extent to which hearing loss affects other executive functions is required to identify the underlying cause of atypical attention in hearing-impaired children. This knowledge may provide insights into novel strategies by which auditory attention could be restored in hearing-impaired children. If directing preparatory attention relies on accurate representations of the cues used to direct attention, focusing on improving those cues may be desirable for future rehabilitation. Whereas, if a wider variety of executive functions are affected by hearing loss, then cognitive training may be more appropriate (see Posner et al., 2015, for a review). The success of these rehabilitation techniques may also depend on whether a critical or sensitive period exists for the development of executive functions. Given there may be individual variability in executive function ability depending on the extent of hearing loss or age of onset, different rehabilitation strategies may be best suited to different individuals. Future experiments should aim to identify whether hearing loss aetiology affects executive function and whether it is possible to restore preparatory brain activity in hearing-impaired children.

5. Conclusion

The results demonstrate that moderate sensorineural hearing loss has consequences for central auditory processing. When presented with a visual cue that directed attention to the location of an upcoming talker, NH children utilised preparatory brain activity. The group of HI children showed significantly weaker evidence of preparatory brain activity than the group of NH children. This result suggests that, on average, HI children do not direct preparatory spatial attention to the same extent as NH children of a similar age. In addition, preparatory spatial attention was not restored when HI children listened using their acoustic hearing aids. Consequently, difficulties with preparatory attention in hearing-impaired children are likely to contribute to difficulties understanding speech in noisy acoustic environments.

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Figure Captions

Fig. 1. Average pure-tone audiometric thresholds (dB HL) for hearing-impaired (HI; N = 14) and normally-hearing (NH; N = 24) children, plotted separately for the left (**A**) and right (**B**) ears. Grey dashed lines show thresholds for individual hearing-impaired participants and the black solid lines show mean thresholds across HI (diamonds) and NH (circles) participants.

Fig. 2. (**A**) Layout of loudspeakers (dark grey squares) and visual display unit (light grey rectangle) relative to a participant's head. Visual cues for location (**B**,**C**) and gender (**D**,**E**). A visual composite stimulus (**F**) was created by overlaying the four visual cues.

Fig. 3. Schematic showing the trial structure in the test condition (**A**) and the control condition (**B**). Stimuli for an example trial are displayed below, with an example of the visual stimuli (left; attend-left trial), acoustical stimuli (centre) and response buttons (right).

Fig. 4. Schematic of EEG analysis pipeline. An example is provided for the comparison between the test and control conditions. (**A**) EEG data were pre-processed and averaged across trials, producing time-locked event-related potentials (ERPs) at each electrode for each participant. (**B**) Spatio-temporal cluster-based permutation analysis was used to extract clusters of electrodes and time points that differed significantly between conditions. An example is shown, in which the scalp map shows the electrodes that contributed to the cluster (red circles), the graph illustrates ERPs at those electrodes, and the dashed box on the graph indicates the time window of each cluster. Time on the x-axis is relative to the onset of the visual cues. (**C**) For each cluster, a bootstrapped null distribution was assembled by selecting, with replacement, samples of NH children of equal size to the

comparison group of HI children. For each sample, the average cluster magnitude was calculated as the difference in amplitude between conditions, averaged across the electrodes and time points that contributed to the cluster. (**D**) The average cluster magnitude in HI children was compared to the bootstrapped distribution from NH children in a two-tailed test.

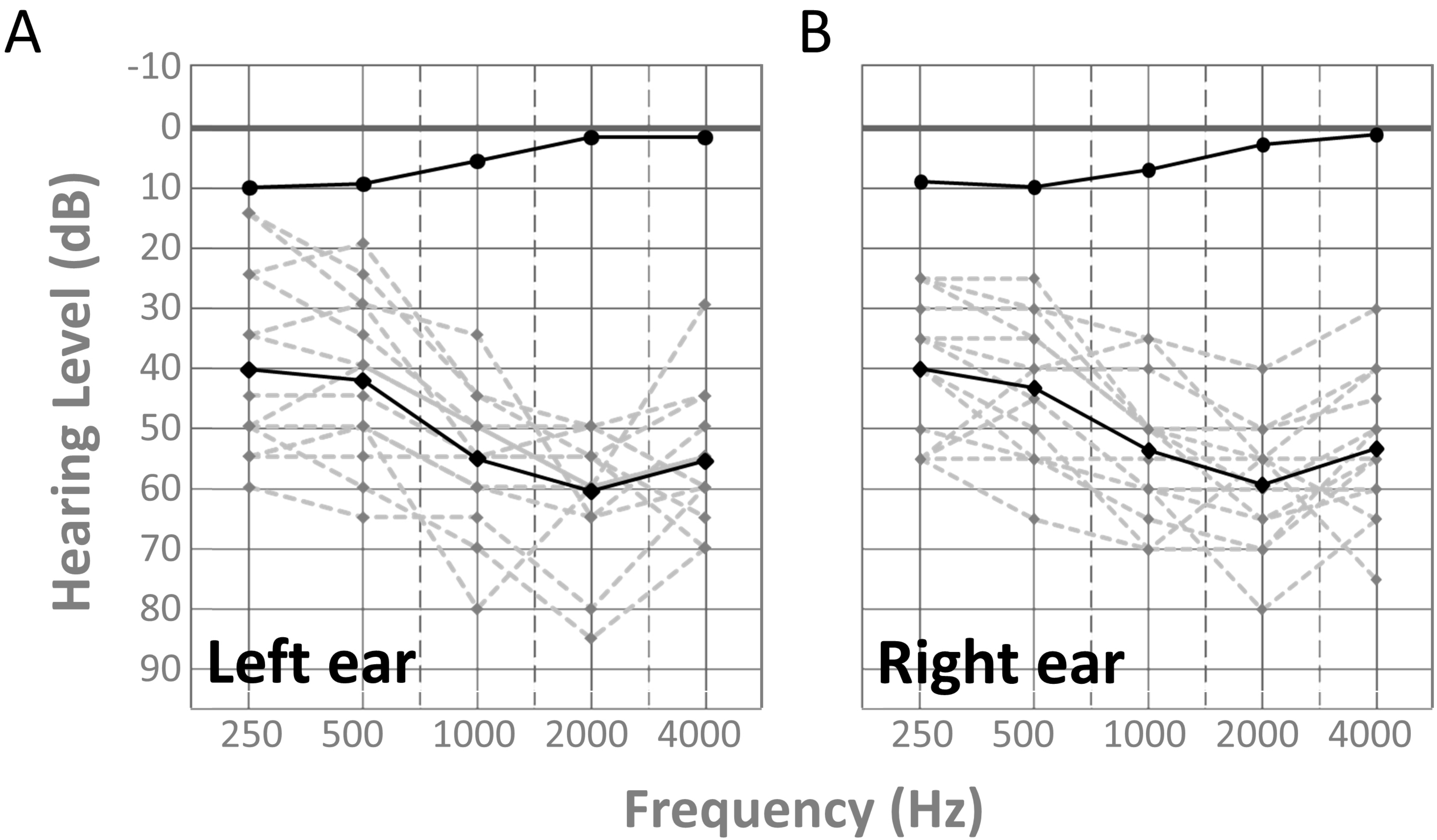
Fig. 5. Mean percentage of trials in which participants correctly identified the colour-number combination spoken by the target talker in the test condition. Separate bars illustrate the results for normally-hearing children (NH; N = 24), hearing-impaired children listening unaided (HI_U; N = 14), and hearing-impaired children listening aided (HI_U; N = 10). Error bars show ±1 standard error of the mean.

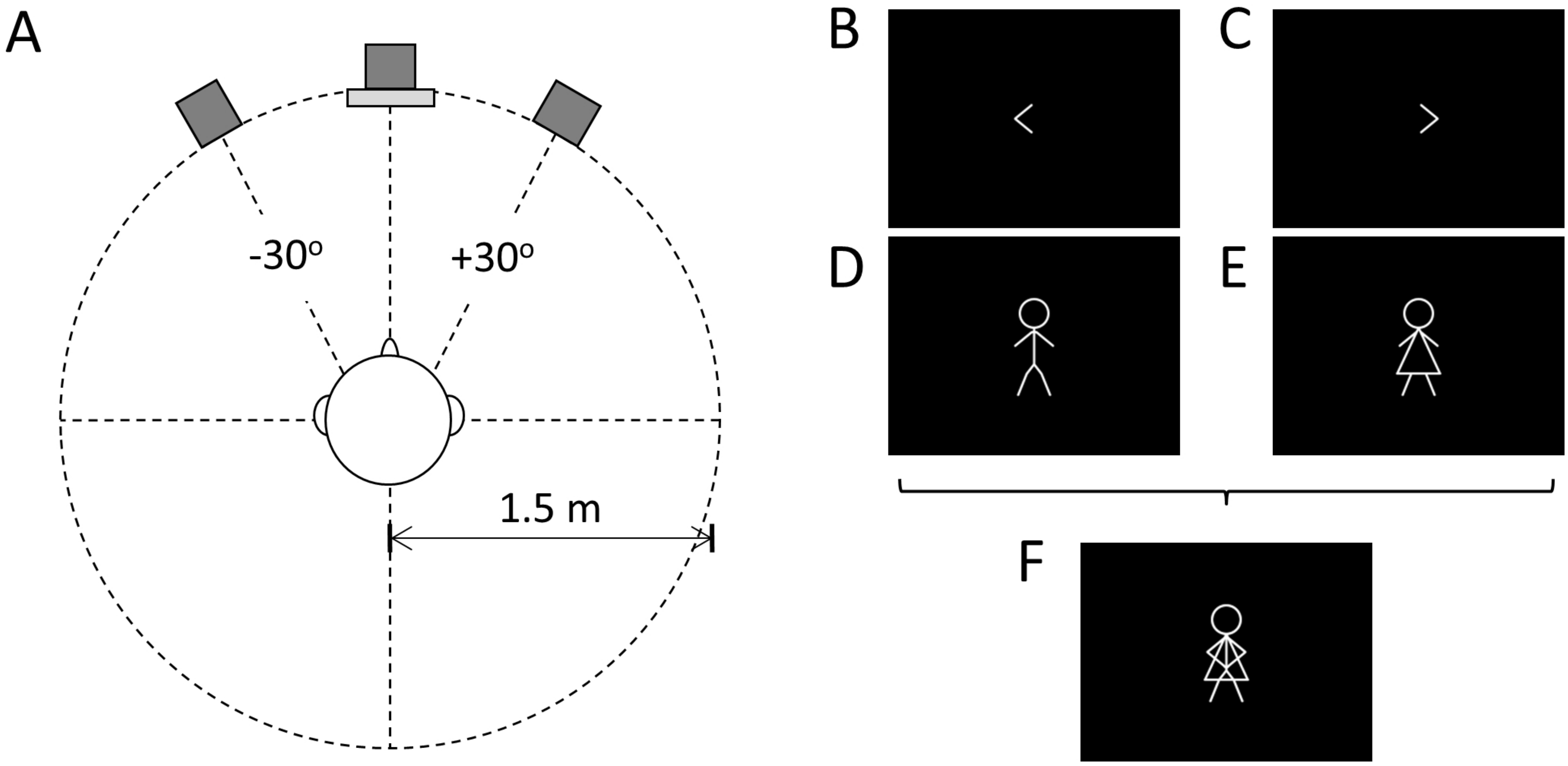
Fig. 6. Results from Spatio-temporal cluster-based permutation analyses in normally-hearing (NH) children for Location (**A**–**D**) and Gender (**E**–**F**) trials. (**A** and **E**) Coloured rectangles indicate the time-span of significant ($p < 0.05$) clusters of activity. Time on the x-axis is relative to the onset of the visual cues. Rows on the y-axis show separate significant clusters. For clusters plotted as red rectangles, the average amplitude, over all space-by-time points in the cluster, was more positive in the test condition than the control condition. For clusters plotted as blue rectangles, the average amplitude was more negative in the test condition than the control condition. Further information about each cluster is displayed in (**B**–**D** and **F**). For each cluster, the topographical map shows the average topography across the time-span of the cluster and black circles superimposed on the topographical map show electrodes that contributed to the cluster. The graph shows ERPs averaged across the electrodes that contributed to the cluster and the dashed grey rectangle indicates the time-span of the cluster.

Fig. 7. Cluster size differed between normally-hearing (NH; N = 24) and hearing-impaired children

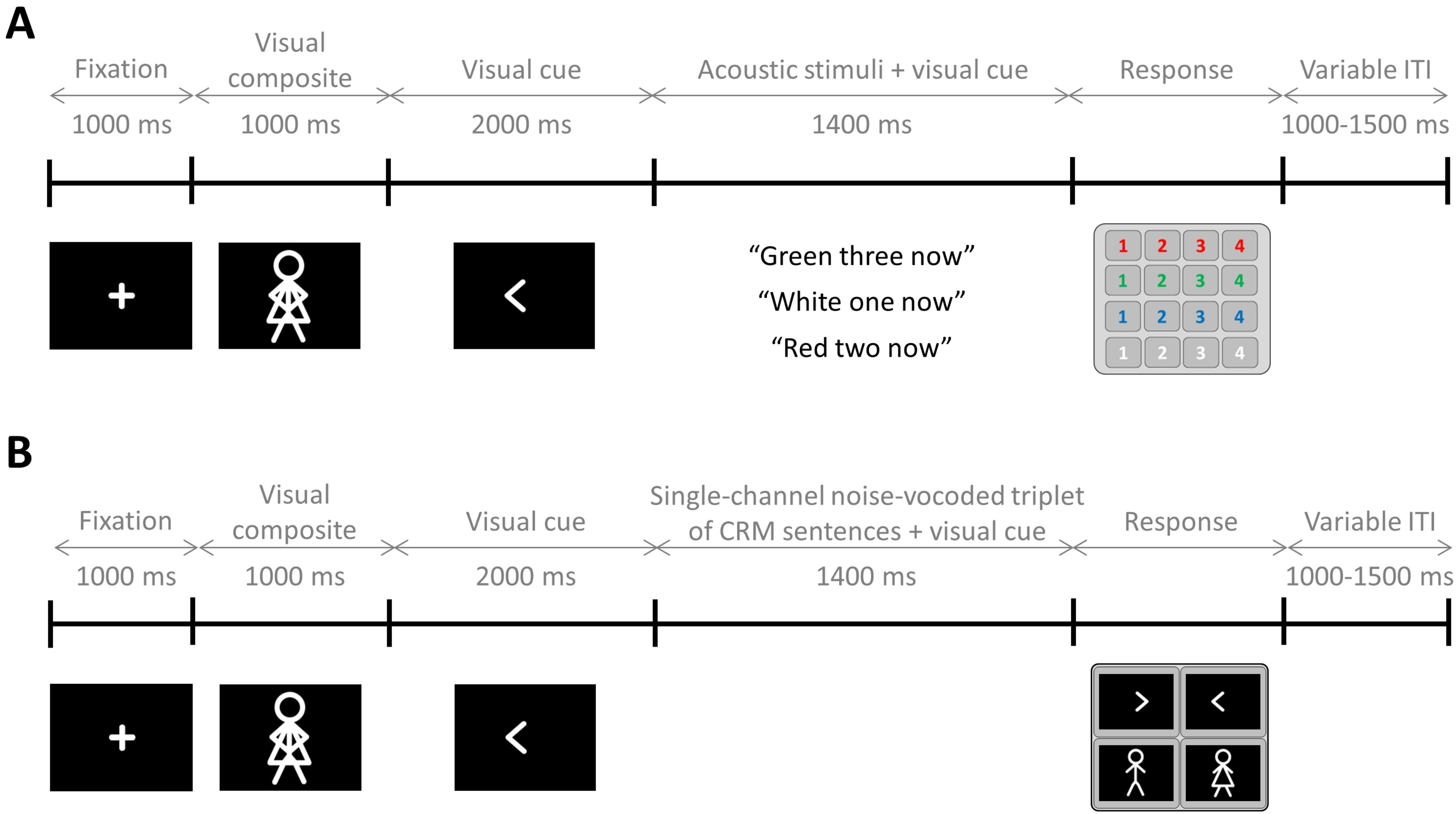
(HI_U; N = 14) for the clusters that occurred during location trials (**A**), but not for the cluster that occurred during gender trials (**B**). For Clusters 2N and 2P, we observed similar results when comparing NH children with the sub-set of hearing-impaired children who completed the task with their hearing aids (HI_A; N = 10). Error bars for HI_U and HI_A children show 95% confidence intervals for each group. Error bars for NH children show 95% confidence intervals from the bootstrapped null distribution. Brackets above each cluster indicate whether there was a significant difference between the groups (* $p < 0.050$; ** $p < 0.010$; *** $p < 0.001$; *n.s.* not significant). The time window of the cluster and the electrodes which contributed are displayed above each cluster.

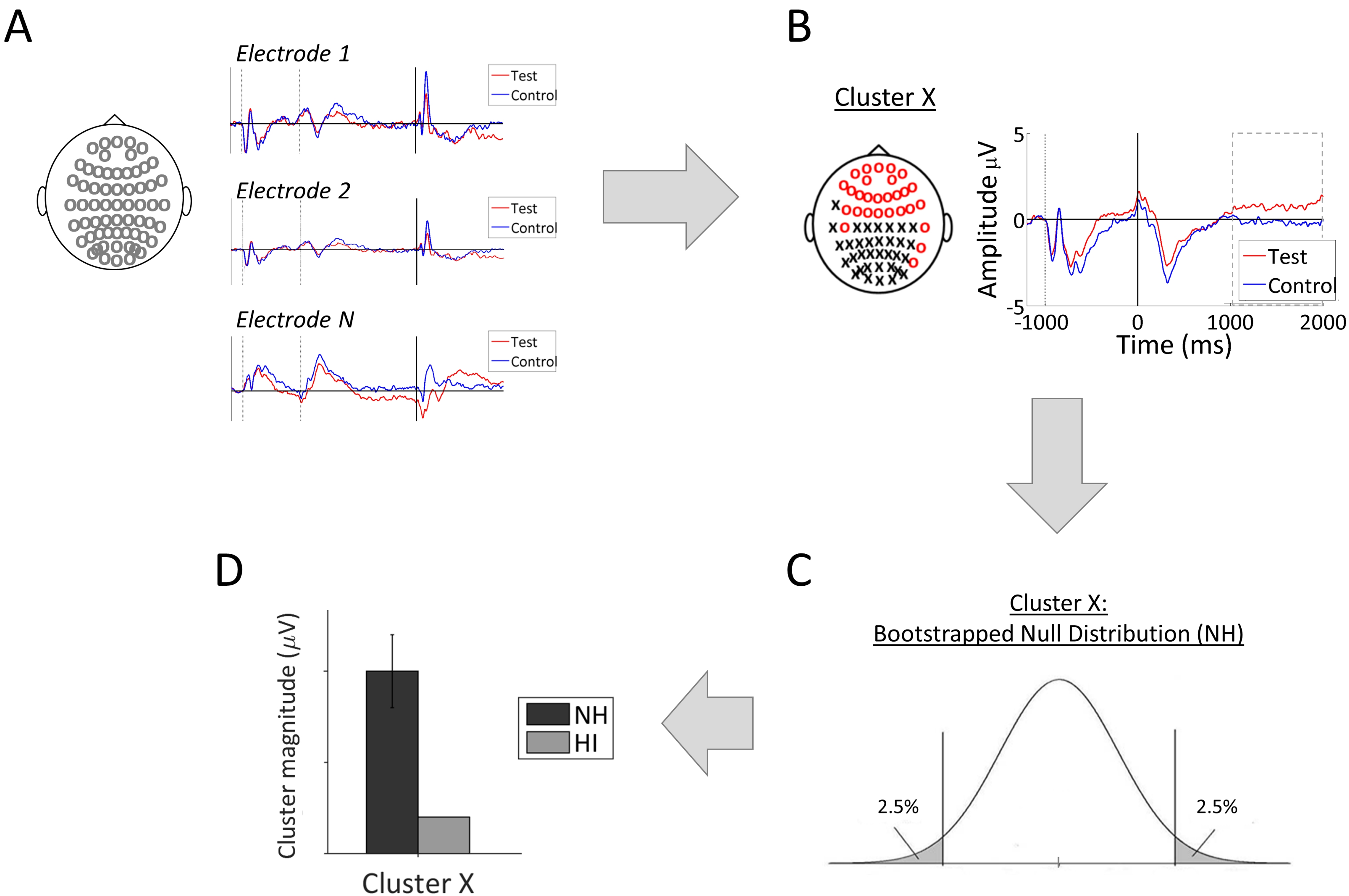
Fig. 8. Results from Spatio-temporal cluster-based permutation analyses in hearing-impaired children (listening unaided; HI_U group) for Location (**A**) and Gender (**B**–**C**) trials. (**A** and **B**) Coloured rectangles indicate the time-span of significant ($p < 0.05$) clusters of activity. Time on the x-axis is relative to the onset of the visual cues. Rows on the y-axis show separate significant clusters. No significant clusters were found for location trials. For clusters plotted as blue rectangles, the average amplitude was more negative in the test condition than the control condition. Further information about each cluster is displayed in (**C**). The topographical map shows the average topography across the time-span of the cluster and black circles superimposed on the topographical map show electrodes that contributed to the cluster. The graph shows ERPs averaged across the electrodes that contributed to the cluster and the dashed grey rectangle indicates the time-span of the cluster. (**D**) Cluster size did not differ signfiicantly between normally-hearing (NH; N = 24) and hearing-impaired children (HI_U; N = 14) for the cluster that occurred during gender trials. The error bar for HI_U children shows the 95% confidence interval. The error bar for NH children shows the 95% confidence interval from the bootstrapped null distribution.


A
B
-10
0
10
20
30
40
50
60
70
80
90
Hearing Level (dB)
Left ear
Right ear
250
500
1000
2000
4000
Frequency (Hz)

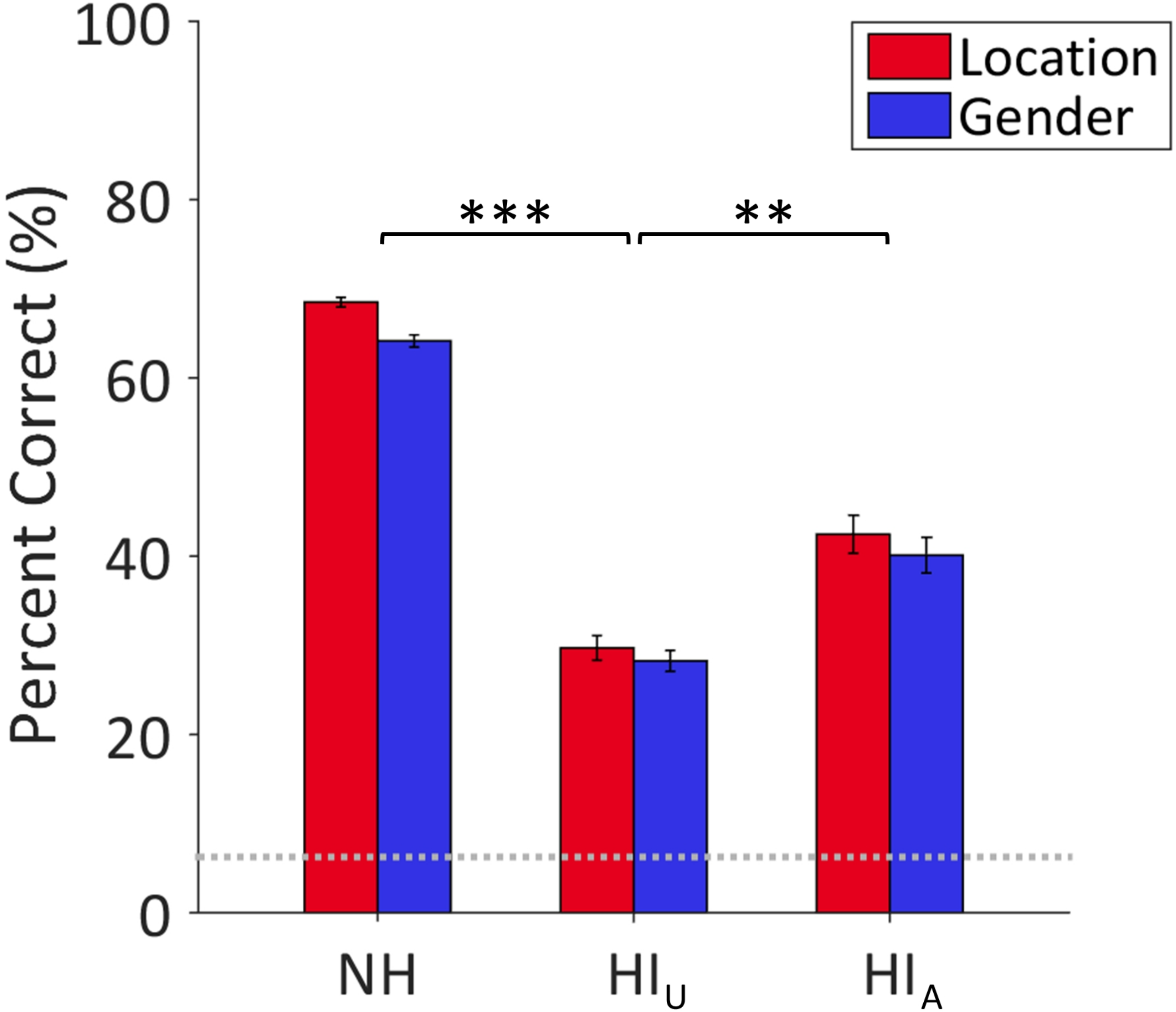


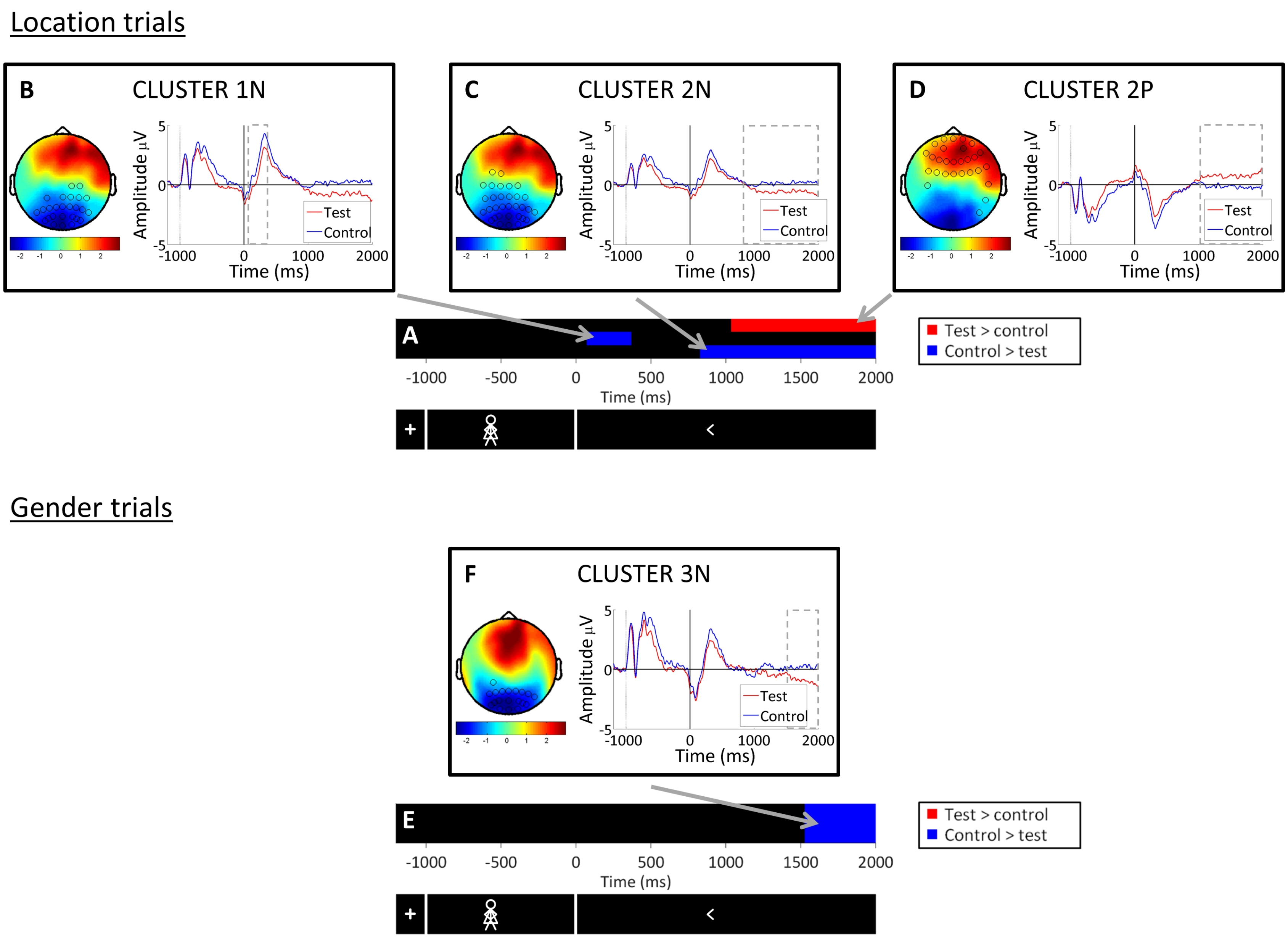
A
-30º
+30º
1.5 m
B
C
D
E
F

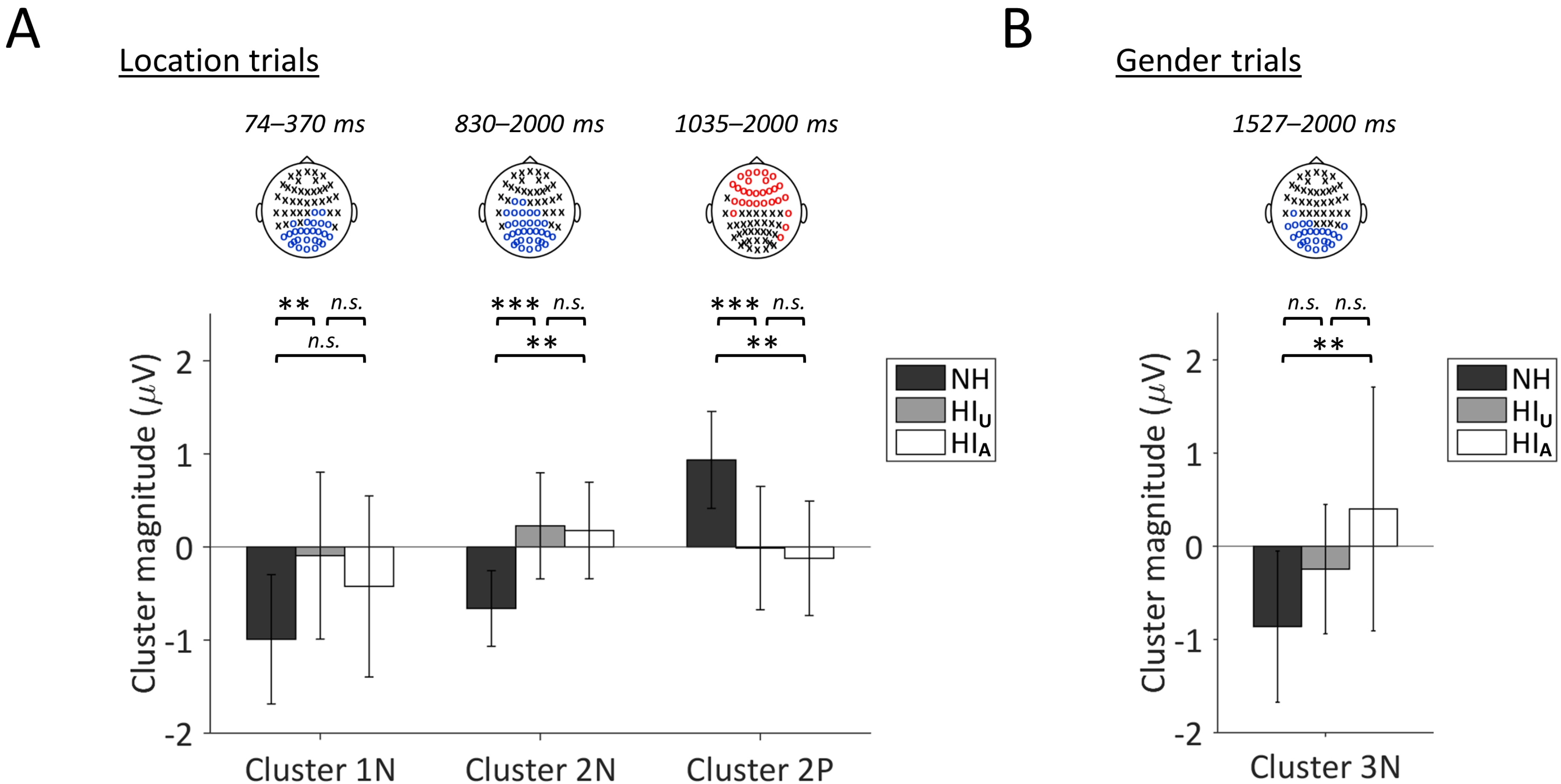

A
Fixation
Visual composite
Visual cue
Acoustic stimuli + visual cue
Response
Variable ITI
1000 ms
1000 ms
2000 ms
1400 ms
1000-1500 ms
+
<
“Green three now”
“White one now”
“Red two now”
1 2 3 4
1 2 3 4
1 2 3 4
1 2 3 4
B
Fixation
Visual composite
Visual cue
Single-channel noise-vocoded triplet of CRM sentences + visual cue
Response
Variable ITI
1000 ms
1000 ms
2000 ms
1400 ms
1000-1500 ms
+
<
>
<



A
Electrode 1
Test
Control
Electrode 2
Test
Control
Electrode N
Test
Control
B
Cluster X
Amplitude μV
5
0
-5
-1000
0
1000
2000
Time (ms)
Test
Control
C
Cluster X:
Bootstrapped Null Distribution (NH)
2.5%
2.5%
D
Cluster magnitude (μV)
NH
HI
Cluster X


Location
Gender
Percent Correct (%)
100
80
60
40
20
0
***
**
NH
HI$_U$
HI$_A$


Location trials
B
CLUSTER 1N
Amplitude µV
Time (ms)
Test
Control
C
CLUSTER 2N
Amplitude µV
Time (ms)
Test
Control
D
CLUSTER 2P
Amplitude µV
Time (ms)
Test
Control
A
-1000 -500 0 500 1000 1500 2000
Time (ms)
Test > control
Control > test
+
<
Gender trials
F
CLUSTER 3N
Amplitude µV
Time (ms)
Test
Control
E
-1000 -500 0 500 1000 1500 2000
Time (ms)
Test > control
Control > test
+
<


A
Location trials
74–370 ms
830–2000 ms
1035–2000 ms
B
Gender trials
1527–2000 ms
**
n.s.
***
Cluster magnitude (μV)
NH
HI_U
HI_A
Cluster 1N
Cluster 2N
Cluster 2P
Cluster 3N

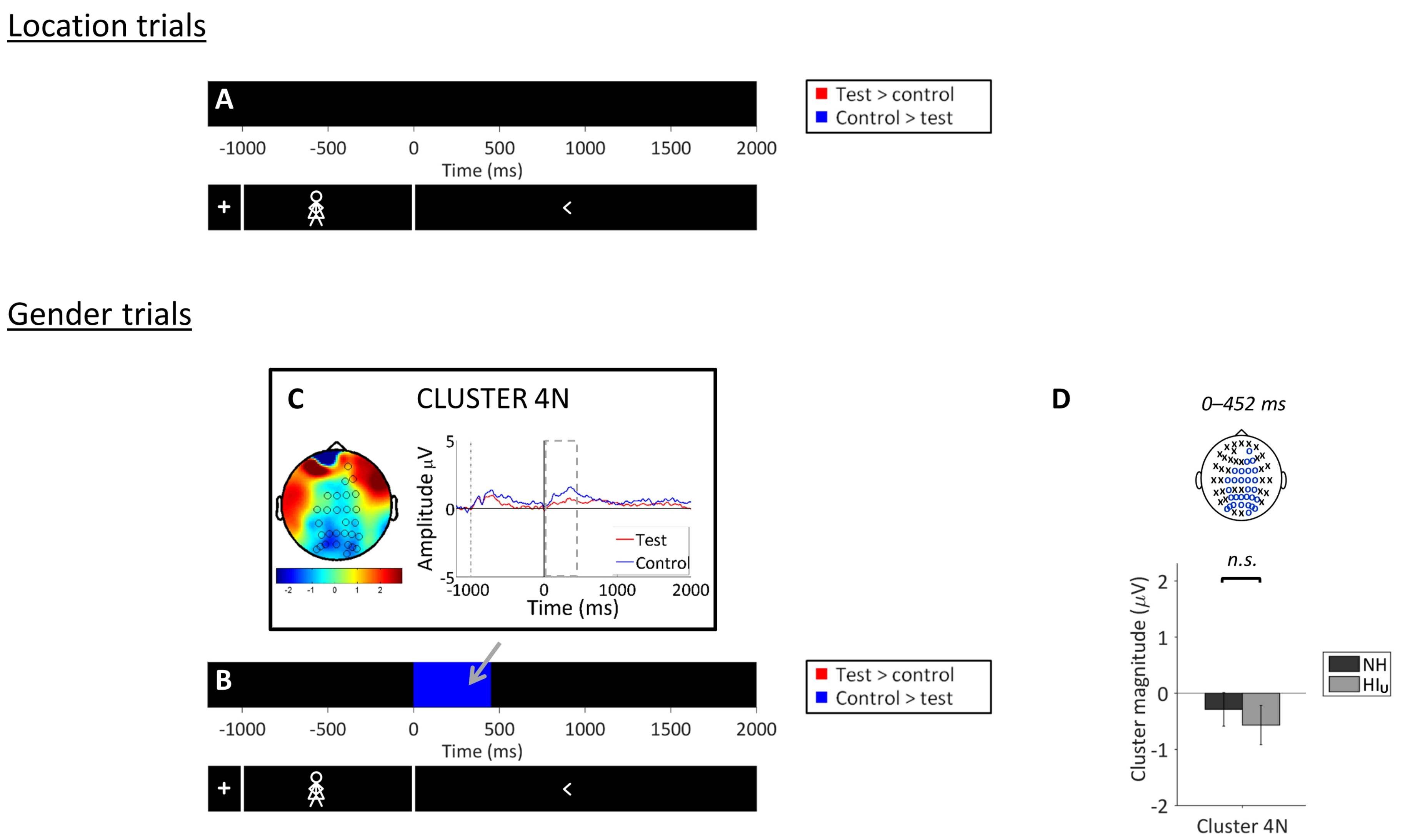

Location trials
A
Test > control
Control > test
-1000
-500
0
500
1000
1500
2000
Time (ms)
+
<
Gender trials
C
CLUSTER 4N
Amplitude μV
Test
Control
Time (ms)
B
Test > control
Control > test
D
0–452 ms
n.s.
Cluster magnitude (μV)
NH
HIU
Cluster 4N

Table 1. Summary of clusters from NH and HI_U children for the Gender and Location Condition comparisons between the Test and Control Conditions. A tick in the row headed 'Difference between NH and HI_U children?' indicates that the difference in the amplitude of ERPs between the Test and Control Conditions was significant between NH and HI_U children across the spatio-temporal points of the cluster using a bootstrapping analysis (p-values displayed underneath). A tick in the row headed 'Difference between NH and HI_A children?' shows the same information for the comparison between NH and HI_A children.

Properties	NH Location	NH Gender	HI_U Location	HI_U Gender
Cluster Number	1N	-	-	4N
Cluster *p*-value	0.040	-	-	0.029
Polarity	Control > Test	-	-	Control > Test
Electrode Locations	Posterior	-	-	Central + Posterior
Onset of cluster (ms)	74	-	-	0
Duration of cluster (ms)	296	-	-	452
Difference between NH and HI_U children?	✓ $p = 0.002$	-	-	✗ $p = 0.08$
Difference between NH and HI_A children?	✗ $p = 0.14$	-	-	-
Cluster Number	2N	3N	-	-
Cluster *p*-value	< 0.001	0.024	-	-
Polarity	Control > Test	Control > Test	-	-
Electrode Locations	Posterior	Posterior	-	-
Onset of cluster (ms)	830	1527	-	-
Duration of cluster (ms)	1170	473	-	-
Significant in HI_U children?	✓ $p < 0.001$	✗ $p = 0.13$	-	-
Significant in HI_A children?	✓ $p = 0.001$	✓ $p = 0.009$	-	-
Cluster Number	2P	-	-	-
Cluster *p*-value	0.003	-	-	-
Polarity	Test > Control	-	-	-
Electrode Locations	Anterior	-	-	-
Onset of cluster (ms)	1035	-	-	-
Duration of cluster (ms)	965	-	-	-
Significant in HI_U children?	✓ $p < 0.001$	-	-	-
Significant in HI_A children?	✓ $p = 0.002$	-	-	-

Highlights

- Participants were cued to attend to one talker in the presence of two other talkers
- We used EEG to measure brain activity in children with and without hearing loss
- Hearing-impaired children showed less evidence of preparatory brain activity
- Preparatory brain activity was not restored when using acoustic hearing aids

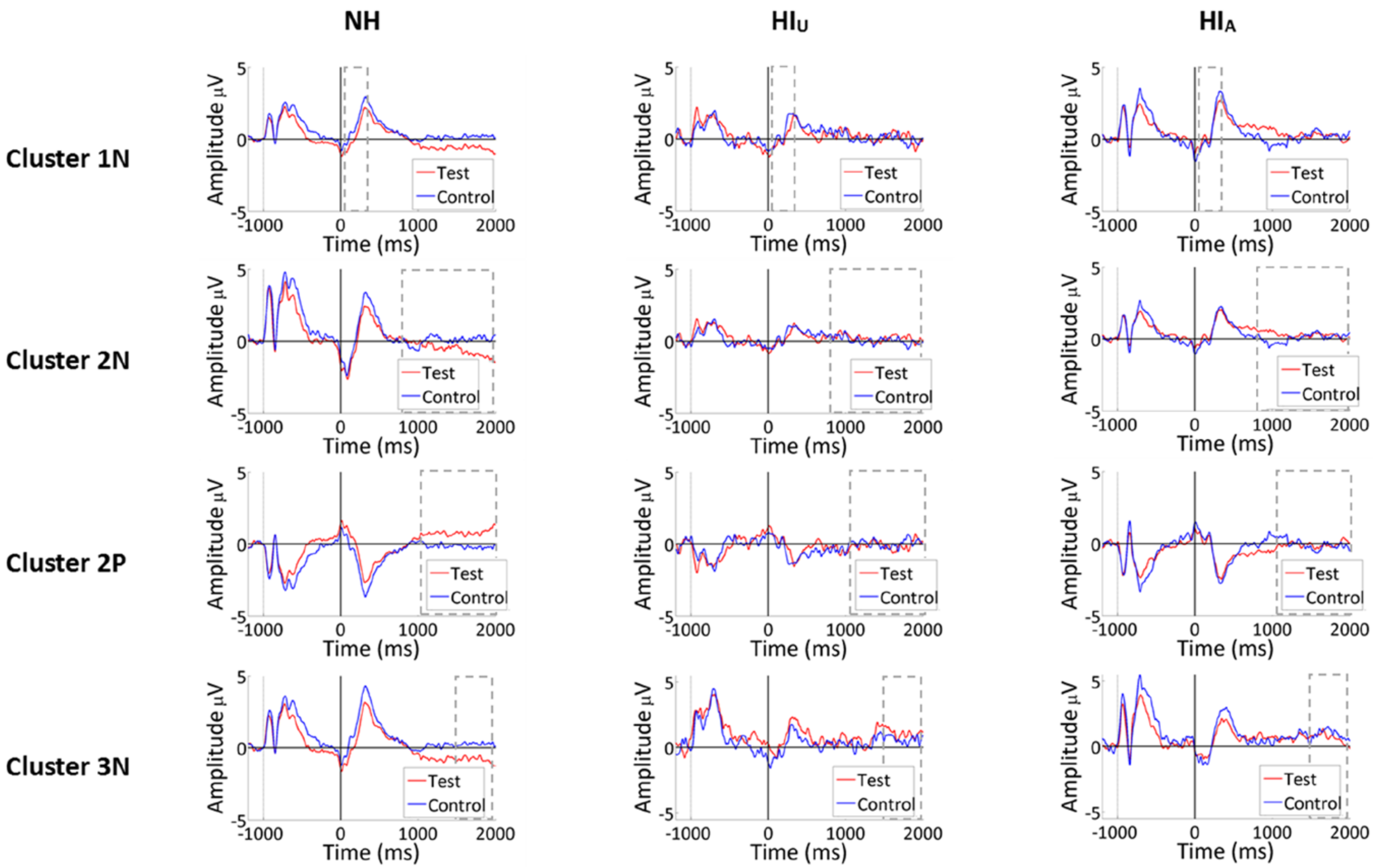


Fig. S1. Comparison of event-related potentials (ERPs), averaged across the electrodes that contributed to each cluster, between hearing groups. Each row illustrates a different cluster and each column illustrates ERPs for a different hearing group: NH = normally-hearing children (N = 24), HI_U = hearing-impaired children without hearing aids (N = 14), HI_A = hearing-impaired children with hearing aids (N = 10). Within each plot, the x-axis is relative to the onset of the visual cue and the grey rectangle indicates the time-span of the cluster.

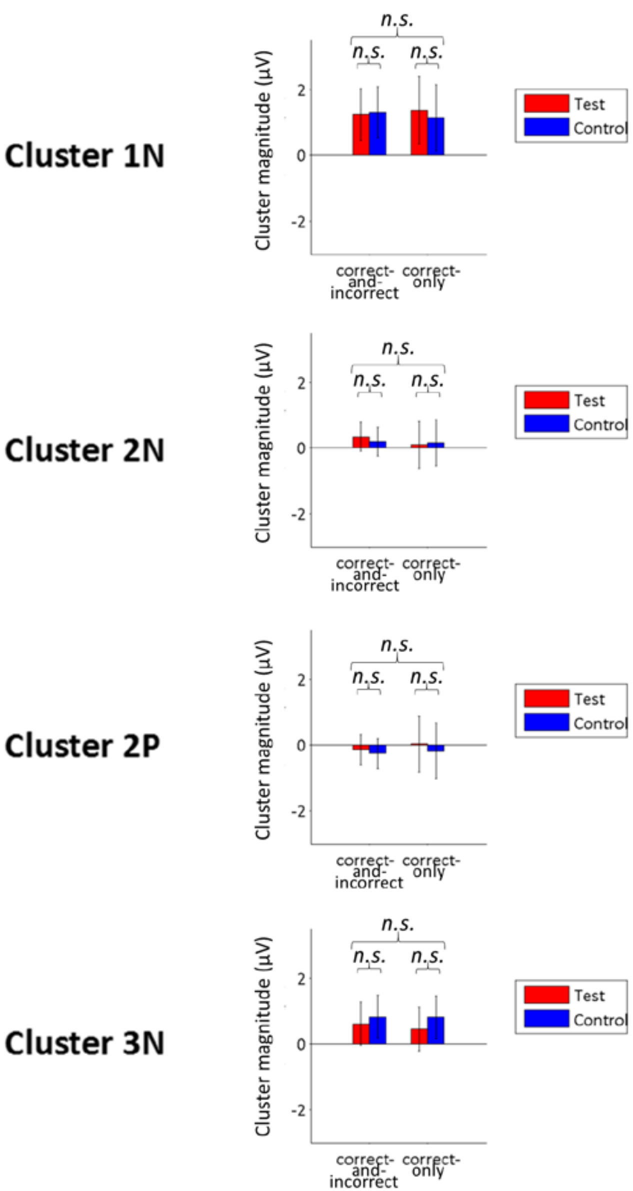


Fig. S2. Comparison of correct-and-incorrect and correct-only analyses in HI_U children (hearing-impaired children performing the task without hearing aids, N = 14). Each bar graph shows the amplitude of each cluster (averaged across the electrodes and time points that contributed to the cluster) in the test and control conditions, plotted when correct and incorrect trials are included in the analysis (“correct-and-incorrect”) and when only correct trials are included in the analysis (“correct-only”). Error bars show 95% within-subjects confidence intervals. Narrow brackets display the significance level of the comparison between the test and control conditions. Wider brackets display the significance level of the two-way interaction (*p < 0.050; **p < 0.010; ***p < 0.001).