Visual Cross-Modal Re-Organization in Children with Cochlear Implants

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Abstract

Background
Visual cross-modal re-organization is a neurophysiological process that occurs in deafness. The intact sensory modality of vision recruits cortical areas from the deprived sensory modality of audition. Such compensatory plasticity is documented in deaf adults and animals, and is related to deficits in speech perception performance in cochlear-implanted adults. However, it is unclear whether visual cross-modal re-organization takes place in cochlear-implanted children and whether it may be a source of variability contributing to speech and language outcomes. Thus, the aim of this study was to determine if visual cross-modal re-organization occurs in cochlear-implanted children, and whether it is related to deficits in speech perception performance.

Methods
Visual evoked potentials (VEPs) were recorded via high-density EEG in 41 normal hearing children and 14 cochlear-implanted children, aged 5–15 years, in response to apparent motion and form change. Comparisons of VEP amplitude and latency, as well as source localization results, were conducted between the groups in order to view evidence of visual cross-modal re-organization. Finally, speech perception in background noise performance was correlated to the visual response in the implanted children.

Results
Distinct VEP morphological patterns were observed in both the normal hearing and cochlear-implanted children. However, the cochlear-implanted children demonstrated larger VEP amplitudes and earlier latency, concurrent with activation of right temporal cortex including auditory regions, suggestive of visual cross-modal re-organization. The VEP N1 latency was negatively related to speech perception in background noise for children with cochlear implants.
Conclusion

Our results are among the first to describe cross-modal re-organization of auditory cortex by the visual modality in deaf children fitted with cochlear implants. Our findings suggest that, as a group, children with cochlear implants show evidence of visual cross-modal recruitment, which may be a contributing source of variability in speech perception outcomes with their implant.

Introduction

Recent advances in cochlear implantation have allowed many children who are born with or acquire severe to profound hearing loss to have accessibility to auditory input and develop speech perception and oral language skills. However, understanding why some implanted children are able to perform at age-appropriate levels while others remain delayed in aspects of speech and language development is critical for clinical intervention, and a focus in research studies [1, 2, 3, 4, 5, 6].

Several factors have been identified that account for significant amounts of variance in speech perception outcomes for cochlear-implanted children. Some of these factors include socioeconomic status, rehabilitative communication strategy, duration of deafness, and age of implantation [2, 7, 8, 9, 10, 11, 12]. For example, we know that age of implantation is a critical factor for harnessing the height of cortical plasticity and for allowing auditory cortical maturation to progress appropriately. The end of the sensitive period for cochlear implantation coincides with the peak of synaptic density in auditory cortex, an indication of maximal plasticity, at approximately 3.5 years of age [13, 14, 15, 16]. Implantation within this time frame results in higher speech perception and language performance outcomes in children [2, 3, 10, 17, 18, 19, 20]. However, despite the identification of key variables important to speech perception and language outcomes, such as sensitive periods for auditory cortical development, a great deal of variance in auditory skill development remains unexplained in children with cochlear implants [3, 21].

Research in profoundly deaf animals and adult humans has described a neurophysiological phenomenon that takes place in auditory deprivation, known as visual cross-modal re-organization [22, 23, 24, 25, 26, 27, 28, 29, 30]. For example, if the cortex is deprived of auditory input during development, specifically before speech and language skills mature, there exists a distinct possibility that the visual cortex will recruit auditory cortical areas for visual processing [22, 24, 25, 26, 31]. However, such compensatory plasticity may pose a challenge for the introduction of audition via a cochlear implant due to the potentially limited resources that may remain for the processing of auditory information [32, 33, 34, 35, 36, 37]. Indeed, adult cochlear implant research literature has described that cross-modal re-organization from the visual modality is linked to deficits in speech perception performance [32, 33, 34, 35, 36, 37], suggesting that this may be another variable influencing speech perception and oral language outcomes in cochlear implanted children.

The purpose of this study was to investigate whether visual cross-modal re-organization is evident in deaf children fitted with cochlear implants and whether this form of compensatory re-organization is related to speech perception outcomes with the implant. We recorded visual evoked potentials via high-density EEG in normal hearing and cochlear-implanted children and performed source localization analyses to observe responsive cortical regions. We then measured speech perception performance in background noise and correlated it with the visual response of the cochlear-implanted children.
Methods

Participants

Subjects included 16 cochlear-implanted (CI) children between the ages of 4.95 and 15.43 years. Two children who had additional diagnosis of CHARGE syndrome and Auditory Neuropathy Spectrum Disorder (ANSD) were not included in the study due to compromised neurological processing. Thus, a total of 14 cochlear-implanted children remained in the analysis (see Table 1). Eleven of the 14 cochlear-implanted children had bilateral cochlear implants, and 3 were unilaterally implanted with a hearing aid on the contralateral ear. Two siblings (CI9 and CI10), had a diagnosis of enlarged vestibular aqueduct syndrome (EVAS), associated with progressive hearing loss. The average implant age of the first ear was 3.12 years (standard deviation = +/-2.27 years, range = 0.5–8.42 years), and average age of implantation of the second ear was 6.20 years (standard deviation = +/-3.45 years, range = 1–13.18 years). The EEG and speech perception testing took place at least 1.5 years post-implantation of the first ear to ensure that cortical changes and speech perception were relatively stable. Results from the implanted children were compared to a group of 41 normal hearing children (NH) spanning an approximately similar chronological age range (5.87–14.53 years). All testing was done at the University of Colorado. The University of Colorado Institutional Review Board approved the study, and the parents of all children provided written consent along with the child’s verbal and/or written assent, dependent upon the age of the child. Participants were recruited through advertisements in the community and their parents reported no neurological conditions and normal to corrected vision (i.e., a few children wore glasses).

Visual Stimuli

All children were shown a high contrast sinusoidal concentric grating that continually transitioned back and forth into a radially modulated grating or circle-star pattern [33, 38, 39, 40] on a 26-inch flat-screen LCD television at a viewing distance of approximately 42 inches. The circle and star figures were presented 150 times. The star grating was present for 600 ms and was immediately followed by the circle grating, also observable for 600 ms. The morphing of the

Table 1. Demographic Characteristics of Cochlear-Implanted (CI) Children.

| Subject | Age | Age at First CI | Age at Second CI | Duration of First CI Experience | Duration of Second CI Experience |
|---------|-----|-----------------|-----------------|---------------------------------|---------------------------------|
| CI1     | 12.46 | 2.67            | 5.42            | 9.79                            | 7.04                            |
| CI2     | 12.39 | 1.00            | 3.33            | 11.39                           | 9.06                            |
| CI3     | 13.13 | 0.50            | 8.09            | 12.63                           | 5.04                            |
| CI4     | 15.43 | 1.41            | 9.26            | 14.02                           | 6.17                            |
| CI5     | 9.40  | 1.99            | 4.36            | 7.41                            | 5.04                            |
| CI6     | 6.89  | 2.28            | 2.90            | 4.61                            | 3.99                            |
| CI7     | 5.84  | 4.33            | Hearing Aid     | 1.51                            | N/A                             |
| CI8     | 11.41 | 1.61            | 6.61            | 9.80                            | 4.8                             |
| CI9     | 13.79 | 8.42            | 13.18           | 5.37                            | 0.61                            |
| CI10    | 11.42 | 6.14            | Hearing Aid     | 5.28                            | N/A                             |
| CI11    | 11.58 | 4.38            | 8.38            | 7.20                            | 3.20                            |
| CI12    | 6.44  | 1.23            | 2.98            | 5.21                            | 3.46                            |
| CI13    | 7.42  | 5.10            | Hearing Aid     | 2.40                            | N/A                             |
| CI14    | 8.68  | 2.50            | 6.38            | 6.18                            | 2.30                            |

Ages and duration of experience are in years.

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circle-star pattern provided the percept of apparent motion and shape change to the viewer, theoretically activating the dorsal (‘where’) and ventral (‘what’) visual networks [33, 38, 40, 41]. A total of 300 stimulus presentations were presented, resulting in a recording period of three minutes. The visual evoked potential (VEP) was time-locked to the onset of each star and circle grating. The children were instructed to direct their gaze to the center of the pattern at a black dot during the three minutes. Overall, the children were able to accomplish the task, and any spurious eye artifacts, such as saccades, were removed during EEG analyses.

**EEG Recording and Analyses**

All children were fitted with a 128-channel EEG electrode recording net (Electrical Geodesics, Inc.). Children with cochlear implants removed the external processor during testing. Complex visual stimuli were presented via E-Prime® 2.0, stimulus software compatible with Net Station 4 (Electrical Geodesics, Inc.). The sampling rate for the EEG recordings was 1 kHz, with an online band-pass filter set at 0.1–200 Hz.

The EEG recordings of each child were high-pass filtered offline at 1 Hz and segmented around each stimulus presentation, with 100 ms pre-stimulus and 495 ms post-stimulus time, then exported from Net Station into EEGLAB [42] using MatLab® (The MathWorks®, Inc., 2010). The data were baseline-corrected to the pre-stimulus period of -100 to 0 ms, and noisy channels were removed from the recording. Artifact rejection set at +/- 100 μV was applied to visual EEG, and data were down-sampled to 250 Hz, altering the post-stimulus time to 492 ms. Data were then re-referenced using common average reference and averaged, and removed channels were replaced with interpolated data via a spherical interpolation algorithm. Finally, the average VEP signal at seven electrodes in the central occipital region [43, 44] were averaged together (70 or O1, 71, 74 and 75 or Oz, 76, 82, and 83 or O2) to create a region of interest (ROI) from which amplitude and latency of VEP peaks for the averaged response were measured. VEP amplitude measurements were recorded as follows: P1 amplitude was measured from P1 peak to N1 peak amplitude, N1 amplitude from N1 peak to P2 peak amplitude, and P2 amplitude from P2 peak to the P2 peak offset amplitude [39, 45, 46, 47]. In the case of a multi-peak VEP, P1 amplitude was measured from the P1 peak to N1a peak amplitude, N1a amplitude from N1a peak to P2a peak amplitude, P2a amplitude from P2a peak to N1b peak amplitude, N1b amplitude from N1b peak to P2b peak amplitude, and P2b amplitude from P2b peak to the P2b peak offset amplitude. Peak latency was defined at the midpoint of the peak. Individual waveforms were averaged together to create a grand-averaged waveform for each group (NH and CI). Group VEP waveforms were low-pass filtered offline at 30 Hz for figure presentation purposes only.

**Current Density Reconstruction**

Individual subject concatenated EEG data underwent independent component analysis (ICA) in EEGLAB following artifact rejection and common average referencing [39, 43, 48, 49, 50]. ICA is a statistical procedure that identifies spatially fixed and temporally independent components that underlie the evoked potential [51], and has been successfully utilized to determine cortical sources, including those in cochlear implanted children [39, 43, 49, 50, 52, 51, 53]. Thirty-two independent components underlying the VEP waveform were produced for each subject. Independent components consisting of artifact, such as eye blinks and electrical noise, were rejected. Next, the percent variance of the remaining independent components underlying the VEP peak of interest was calculated in EEGLAB [42]. Only independent components accounting for a majority of the percent variance in the peak of interest were retained and exported into CURRY® Scan 7 Neuroimaging Suite (Compumedics Neuroscan™) for source
modeling. In CURRY, the individual participant ICA-pruned data were averaged into groups corresponding to the peak component of interest (e.g. P1 in cochlear-implanted children), and a second ICA was computed on the pruned components from the first ICA analysis to remove additional component artifacts.

Current density reconstructions (CDR) were created for the VEP components using standardized low-resolution brain electromagnetic tomography (sLORETA). sLORETA consists of statistical analyses that include the variance of the cortical generator(s) as well as underlying variance due to recording artifact to produce images (CDR) depicting statistically likely areas within the cortex producing post-synaptic electrical activity [54, 55]. Head models for sLORETA analyses were created using Boundary Element Method (BEM) geometry [56] in CURRY based upon developmental white matter averages in children provided by Wilke et al. [50, 57]. The sLORETA output, or CDR F-Distribution, was represented by a scaled color image. The image was placed on a Montreal Neurological Institute (MNI) child MRI. Sagittal MRI slices were selected to illustrate each CDR.

Speech Perception in Noise

Speech perception in background noise was measured using the BKB-SIN™ test [58, 59], a clinical assessment of the ability to perceive speech in background noise [60]. Children faced a speaker that was placed at 0° azimuth and repeated two recorded sentence lists (six sentences each) presented at 65 dB Hearing Level (HL). Background noise was increased in 5 dB steps from 25 dB signal-to-noise ratio (SNR) to 0 SNR. The SNR level at which the child could repeat 50% of the sentences was calculated and recorded as threshold. The lower the SNR threshold, the better the performance on the test. Recommended corrections were applied to SNR threshold values to account for differences in processing ability due to age [59]. Cochlear-implanted children wore their implant(s), and if applicable, hearing aid, programmed to their usual settings. SNR threshold values were recorded for 13 of the 14 CI children (one child, CI14, was unable to complete testing) and 27 of the 41 NH children. There was no significant difference in age between the group of CI and NH children who underwent BKB-SIN testing ($t(38) = 0.234, p > 0.05$).

Results

Visual Evoked Potentials

Both NH and CI children demonstrated two morphological patterns of VEP responses (Figs 1–3), which are described below. Given that in previous studies, we have found no developmental differences between the two VEP pattern morphologies in NH children, we created grand average waveforms of each pattern for NH and CI children. Pattern A consisted of three obligatory VEP peak components: P1, N1, and P2. Peak components for pattern A were identified as follows: P1 as the first positive peak occurring at approximately 100 ms, N1 as the first negative peak at approximately 270 ms, and P2 as the second positive peak occurring at approximately 360 ms. The second pattern, pattern B, consisted of multiple peaks labeled as P1, N1a, P2a, N1b, and P2b. Peak components for pattern B were identified as follows: P1 as the first positive peak occurring at approximately 100 ms, N1a as the first negative peak occurring at approximately 200 ms, P2a as the second positive peak occurring at approximately 250 ms, N1b as the second negative peak occurring at approximately 300 ms, and P2b as the third positive peak at approximately 360 ms. VEP morphology similar to that of pattern B (which differs from the typical P1-N1-P2 response) has been identified in the developmental VEP literature, and described in typically developing, non-clinical pediatric populations [40, 61, 62]. Seven CI children (50%) and 16 NH children (39%) presented with pattern A, while 7 CI children (50%)
and 25 NH children (61%) presented with pattern B morphology. For each morphological pattern, latencies and amplitudes were compared using the Mann-Whitney U test for one-way ANOVAs [63] and the Kruskall Wallis H test for pairwise comparisons. The Bonferroni correction was used in the case of multiple comparisons.

Fig 1 illustrates the two VEP morphological patterns observed in the CI children. There was no significant difference in age between the children that exhibited pattern A (mean age and standard deviation = 10.79 +/- 3.51 years, range = 5.84–15.43 years) and pattern B responses (mean age and standard deviation = 10.11 +/- 2.64 years, range = 6.44–13.79 years) ($t(12) = 0.413, p > 0.05$). Further, as seen in Fig 1, the P2a peak component in Pattern B is significantly earlier than the P2 peak in Pattern A ($\chi^2(2) = 3.297, p = 0.003$). This finding indicates that the P2a peak in Pattern B of the CI children possibly occurs as an additional independent
component, and that Patterns A and B are distinct from one another, consistent with NH children tested in previous studies in our laboratory.

Fig 2 depicts the comparison between the VEP pattern A response of NH and CI children. There was no significant difference in age between the two groups for this pattern ($t(21) = -0.719, p > 0.05$). There was no significant difference between P1, N1 and P2 component latencies or amplitudes for the NH and CI children exhibiting pattern A responses, although the N1 shows an observable trend towards an earlier latency and larger amplitude in the CI children.

Fig 3 shows the comparison between the VEP pattern B response of NH and CI children. There was no significant difference between age for the two groups ($t(30) = 0.454, p > 0.05$). While there was no significant difference in P1, N1 and P2 latencies between the two groups, N1a amplitude was significantly greater in the CI group ($U = 147, Z = 2.712, p = 0.005$), as was
P2b amplitude ($U = 140, Z = 2.393, p = 0.015$). This finding is consistent with studies that have shown larger VEP responses for adults with hearing loss (including cochlear implant users) relative to age-matched normal hearing subjects [32, 33, 39, 64, 65].

**Current Density Reconstruction**

Current density reconstruction (CDR) was performed using standardized low-resolution brain electromagnetic tomography (sLORETA) for all VEP components. In order to maximize the number of subjects and statistical power needed to accurately examine visual cortical activation for NH and CI children, similar underlying peak components (as identified through ICA) were
combined across VEP patterns and used for CDR analyses. For example, the independent com-
ponents comprising the P1 peak in the pattern A VEP response were combined with the inde-
pendent components underlying the P1 peak in the pattern B VEP response for NH and CI
children separately. The same procedure was followed for combining the N1 in pattern A and
the N1a in pattern B, the N1 in pattern A and N1b in pattern B, and the P2 in pattern A with
the P2b in pattern B. As described previously, given that the P2a in pattern B was statistically
different from the P2 component in pattern A, the components of these two peaks were not
combined. Resulting CDR activations were plotted on an average MRI (sagittal slice view) and
the MNI co-ordinates designated beneath each slice. The F-Distributed scale, indicating the
strength of the cortical response, is also shown. Cortical regions are listed according to approxi-
mate order of response strength in the table to the right of each panel.

Fig 4 (Panels A and B), shows the cortical generators in response to visual stimuli for CI
children in comparison to NH children. The underlying sources of the VEP P1 peak compo-
nent are similar for the two groups, with both cerebellar, striate, and extrastriate activations,
including cuneus, lingual gyrus, and Brodmann areas 18 and 19. These activations are consist-
tent with other visual imaging studies in adults and children using visual stimuli similar to ours
[38, 39, 66, 67]. For the N1/N1a and N1/N1b combined components, it can be observed that
the CI children, in addition to normal occipital activation, demonstrated a response in the
right lateral temporal cortex. This response was notably absent in the left hemisphere. Right
temporal visual cortical activation included superior temporal gyrus, medial temporal gyrus,
inferior temporal gyrus, and Brodmann Area 22. These areas were not activated in the NH chil-
dren, who demonstrated the expected cerebellar and extrastriate responses generating the N1
components. The additional activation of temporal areas in CI children (not seen for NH chil-
dren) is consistent with studies in profoundly deaf adults and cochlear implanted adults and
has been considered to be indicative of visual cross-modal re-organization [24, 25, 26, 31, 32,
33, 35, 37, 39, 68]. In contrast to the N1 components, the P2/P2b components demonstrated
expected visual cortical responses for both NH and CI children, showing cerebellar, fusiform,
and extrastriate activation. It should be noted that since only seven children showed the P2a
response, we have not included those results in Fig 4. However, the visual sources for the P2a
were very similar to the N1 components, encompassing the ventral visual stream as well as
superior temporal gyrus and Brodmann Area 22. This is expected because the P2a response
appears in the same timeframe as the N1 components (see Fig 1) and may involve similar
underlying independent components.

Speech Perception in Noise

Auditory perception of speech in background noise was measured using the BKB-SIN test [58,
59]. This measure provides a signal-to-noise (dB SNR) threshold, or how much greater the sig-
nal should be in relation to background noise in order for the child to perceive 50% of the
words in a sentence list.

As shown in Fig 5A, the CI children had a significantly higher or worse BKB-SIN threshold
than the NH children ($U = 335, Z = 4.609, p = 0.000$). This result is consistent with studies of
speech perception in background noise in CI children [69, 70]. In order to correlate the audi-
tory performance in background noise with the visual response in the CI children, the VEP N1
was determined to be an appropriate marker of visual cross-modal plasticity. The VEP N1
response (from the right temporal cortex) has been described as a marker for visual cross-
modal plasticity in adults with hearing loss and cochlear implants in previous studies [32, 39],
and showed evidence of visual cross-modal re-organization in the CI children in the present
study (Fig 4). With this in mind, the average VEP signal at five electrodes in the right temporal
Fig 5B shows a significant correlation (Spearman’s rank-order) between BKB-SIN threshold and VEP N1 latency ($r = -0.576, p = 0.02$). In other words, worse speech perception in background noise was associated with decreased N1 latency. Our finding is congruent with results in cochlear-implanted adults and adults with hearing loss, showing a similar relationship between the VEP N1 component and speech perception performance [32, 39]. Finally, there were no significant differences between the CI children demonstrating VEP pattern A relative to pattern B in regard to mean speech perception thresholds ($U = 29, Z = 1.143, p > 0.05$).

Due to the finding of significantly larger P2b amplitude in the implanted children concurrent with a localization of visual cortical generators for this component (Fig 4A and 4B), we
calculated the correlation (Spearman’s rank-order) between the combined VEP P2/P2b amplitude in the occipital ROI in the CI children with BKB-SIN performance. The resulting correlation approached significance ($r = 0.473$, $p = 0.051$). Thus, worse speech perception in background noise was associated with an increase in VEP P2/P2b amplitude in the occipital region, similar to findings in pre-lingually deaf implanted subjects [71, 72].

Discussion

In this study, we examined whether cochlear-implanted children would show evidence of cross-modal cortical re-organization from the visual modality and whether such re-organization may be related to speech perception outcomes with the implant. High-density EEG recordings elicited by radially modulated visual gratings and speech perception in noise performance were compared in cochlear-implanted (CI) and normal hearing (NH) children.

We describe three main findings: (i) Both NH and CI children showed two distinct morphological patterns of the VEP response that appear not to be developmentally significant. (ii) The VEP N1 component in the CI children exhibited clear evidence of activation of right temporal cortex, including auditory areas, suggestive of visual cross-modal plasticity. (iii) Decreased VEP N1 latency, considered a marker for cross-modal re-organization, showed a significant inverse relationship with speech perception in noise outcomes for the CI children.

Converging Evidence for Cross-modal Re-organization From VEP, CDR and Speech Perception

Both the NH and CI children presented with two VEP patterns, illustrating similar morphological development in visual processing of apparent motion and shape change. Pattern A consisted of the typical P1-N1-P2 complex, with a trend toward increased amplitude and decreased latency of the N1 component in the CI children. Pattern B was comprised of a multi-
peak response, with the CI children showing larger N1a and P2b amplitude. Larger VEP amplitude, specifically in the N1 component, has been a consistent finding related to visual cross-modal re-organization in profoundly deaf adults, cochlear-implanted adults, and adults with hearing loss [32, 39, 64, 65]. For example, deaf and cochlear-implanted adults have demonstrated increased VEP N1 amplitude over temporal cortex, or an enhanced visual response in this region [32, 64, 65]. Decreased VEP N1 latency has also been linked to visual cross-modal re-organization in adults with hearing loss [39], likely reflecting underlying synaptic changes of visual cross-modal inputs [23, 27].

The CDR results for the N1 component revealed that visual stimuli activated right temporal cortical sources (in addition to normal occipital visual generators) underlying the N1 component in the CI children, but only activated expected or typical visual cortical areas in NH children. Additional areas activated in the CI children included the right ventral visual stream, which is responsible for the processing of object and facial information, as well as auditory processing areas (including superior temporal gyrus and Brodmann Area 22). It is interesting to note that temporal activation was not observed for the left hemisphere. The right temporal hemisphere appears to be more susceptible to visual cross-modal re-organization and its activation by visual stimuli is consistent with such compensatory plasticity reported for adults with hearing loss and cochlear-implanted patients [24, 25, 26, 31, 32, 33, 35, 37, 39]. The finding of activity in the right ventral visual stream and auditory regions is also in agreement with results reported by Giraud and Lee [73], where resting positron emission tomography (PET) data revealed that pre-implantation activation of ventral maladaptive cortical networks were predictive of poor speech perception post-implantation in cochlear implanted children.

In order to investigate whether the observed visual plasticity in the CI children was related to auditory performance, we presented a subset of both groups with sentences in background noise using the BKB-SIN. The CI children performed significantly worse than the NH children in this task (Fig 5A), and their speech perception in noise thresholds reflected a significant negative correlation with N1 latency. The VEP N1 may demonstrate a faster response in temporal cortex, including auditory regions, due to increased synaptic strength and connections involved in visual cross-modal plasticity [23, 27, 74, 75]. Our finding of an inverse relationship between N1 latency and speech perception are consistent with similar findings in hearing-impaired and implanted adults [32, 37, 39, 68] and suggest that visual cross-modal re-organization may negatively impact speech perception performance. Overall, our results indicate that a greater level of visual cortical activity, extending outside of classic visual areas, is related to decreases in speech perception in children with cochlear implants.

In the present study, the latency and CDR of only the VEP N1 component provided clear evidence of cross-modal re-organization by vision. We found no difference in P1 latency, amplitude or CDR sources between the NH and CI children, consistent with similar reports in studies of adults and children with hearing loss and cochlear implants [33, 39]. It is possible that because the P1 reflects primary visual areas, it is less likely to be involved in cross-modal re-organization [33, 40, 76]. Similarly, the CDR for the VEP P2 showed visual sources for both the NH and CI children. However, the P2b showed significantly larger amplitude for the CI children as compared to the NH children. Given that the P2 reflects higher order visual processing, its possible that the larger amplitude in CI children is suggestive of increased visual intra-modal processing. Interestingly, visual intra-modal plasticity, or an enhanced response within the recruiting modality, has also been found to be predictive of poor speech perception in congenitally deaf cochlear-implanted subjects [71, 72, 73]. Along these lines, when we correlated the peak amplitude of the combined VEP P2/P2b components in the CI children from the visual ROI with their auditory performance in background noise, we found a positive correlation approaching significance. That is, increased visual intra-modal plasticity (as reflected by
both the increased amplitude and CDR results) was related to poor speech perception in background noise, consistent with previous studies in cochlear-implanted subjects with pre-lingual deafness [71, 72, 73]. This finding, along with visual cross-modal re-organization represented by the N1 components in the CI children, is supportive of an overactive visual system being related to poorer auditory outcomes in congenitally deaf children [71,72]. However, in post-lingual deafness, this visual intra-modal plasticity has been shown to be related to higher speech perception outcomes in implanted subjects, possibly indicating different mechanisms underlying visual plasticity in pre- versus post-lingual deafness [37].

**Visual Cross-modal Recruitment of Right Temporal Cortex**

Why is visual cross-modal re-organization of the right temporal cortex implicated in CI children? One reason may be the importance of the right hemisphere ventral visual stream in human facial processing. Subjects who had congenital visual deprivation of the right hemisphere performed more poorly when distinguishing faces than subjects with congenital left hemispheric visual deprivation [77]. In addition, fMRI has shown that the right hemisphere demonstrates a stronger response in both adults and typically developing children during a face-matching task [78]. It is reasonable to assume that in hearing loss, facial processing becomes even more important to satisfy communication needs. Letourneau and Mitchell [79] showed that congenitally deaf adults who use sign language for communication focus equally on bottom and top halves of faces in comparison to normal hearing adults who divided visual attention based on identity or emotion. Behavioral studies in cochlear-implanted children have also revealed the importance of visual facial input during communication. Tyler et al. [80] found that CI children continued to improve in lip-reading several years post-cochlear implantation, while Bergeson et al. [81] reported speech perception performance to be enhanced for CI children when visual cues were also present.

Anatomical changes in the right temporal cortex of subjects with hearing loss may also be related to visual cross-modal re-organization. Structural neuroimaging studies in adults with hearing loss have revealed a loss of gray matter in right auditory cortex [82, 83]. Hearing-impaired adults also show reduced activity in right auditory cortical regions in response to auditory stimuli, concurrent with increased activation of right auditory areas by visual stimuli [39, 43]. Partial or total auditory deprivation may therefore result in a loss or decline of gray matter in auditory regions of the right hemisphere due to lack of stimulation, allowing for greater allocation of resources to visual processing in this area [39, 43].

While evidence of visual cross-modal re-organization appears similar in adults with early-stage, mild-moderate, acquired age-related hearing loss [39], implanted adults with post-lingual deafness [33, 34, 37], and implanted children (as reported in the present study), the underlying mechanisms driving such plasticity are likely different. Cortical plasticity in development is largely driven by extrinsic sensory input, while central auditory and visual pathways have already been created and strengthened in adults with acquired hearing loss [34, 84]. Therefore, visual plasticity as a result of post-lingual hearing loss may be more cognitively-driven (top-down) versus sensory-driven (bottom-up) in pre-lingual deafness [84]. Indeed, cognitive cortical regions are activated by audition in acquired hearing loss, but future studies are needed to ascertain if cognitive cortical regions act as a mediator of visual plasticity [43].

**Synesthesia and Individual Variability**

What might be a proposed mechanism by which visual cross-modal recruitment occurs in cochlear-implanted children? Giraud and Lee [73] have proposed that congenital auditory deprivation leads to a synesthetic state of the cortex. If early auditory experience is not present, the
auditory cortex is not specifically marked for auditory and speech processing, which may allow inherent cross-modal recruitment by other modalities. The authors suggested that cochlear implantation prior to age 1 year may counteract such effects, though additional research in deaf infants is needed to better understand the prevalence and mechanisms underlying cortical synesthesis. In the present study, the average age of the first implant was 3.1 years, which is relatively late and towards the end of the sensitive period of 3.5 years. It is possible that children implanted at earlier ages, as suggested by Giraud and Lee [73] may not show cross-modal recruitment. Future studies are needed with larger numbers of subjects to examine if there is an effect of age of implantation on cross-modal plasticity. Similarly, future research should also consider other factors such as socioeconomic status, unilateral or bilateral implantation, and rehabilitative communication strategy, among others, which would provide useful information in determining the relative importance of visual cross-modal re-organization to functional outcomes.

In any case, it appears that some CI children may be more prone to cross-modal recruitment. In a recent case report, we describe that cross-modal plasticity by both the visual and somatosensory modality was only evident in children who were average or poor performers with their implant and not in children who were good performers with their implants [85]. This individual variability may have implications for rehabilitation in children with cochlear implants including decision-making on appropriate communication approaches. Overall, our study indicates that visual cross-modal re-organization occurs in CI children and is related to performance with the implant, and should therefore be considered as another factor contributing to the variability in auditory outcomes for cochlear-implanted patients.

Summary and Conclusion

Our study provides new evidence demonstrative of visual cross-modal plasticity in a group of deaf children fitted with cochlear implants. Converging evidence in the CI children, including decreased latency and increased amplitude of the VEP N1 components, activation of right hemisphere auditory temporal areas underlying the N1 response, and an inverse relationship between VEP N1 latency and speech perception in noise, suggest that, as a group, children with cochlear implants showed evidence of visual cross-modal plasticity. Future studies are needed to determine the full impact of visual cross-modal compensatory plasticity on rehabilitative outcomes for children with cochlear implants, including pre- and post-implantation measures to investigate whether this plasticity is predictive of success with communication approaches and whether it can be enhanced or reversed with training.

Supporting Information

S1 Table. Speech Perception Performance in Background Noise (BKB-SIN) and VEP N1 Latency Data for Fig 5. (A) Subject numbers. (B) Corresponding mean BKB-SIN threshold values. (C) VEP N1 latency (in milliseconds) as recorded from the right temporal region of interest (ROI) for the cochlear-implanted (CI) children.

(XLSX)

Author Contributions

Conceived and designed the experiments: JC AS. Performed the experiments: JC. Analyzed the data: JC AS. Contributed reagents/materials/analysis tools: JC AS. Wrote the paper: JC AS.
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