

# Cross-modal plasticity in children with cochlear implant: converging evidence from EEG and fNIRS

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# Abstract

Over the first years of life, the brain undergoes substantial organization in response to environmental stimulation. In a silent world, it may promote vision by 1) recruiting resources from the auditory cortex and 2) making the visual cortex more efficient. It is unclear when such changes occur and how adaptive they are, questions that children with cochlear implants (CI) can help address. Here, we examined 7 to 18 years old children: 50 had CIs, with delayed or age-appropriate language abilities, and 25 had typical hearing and language. High-density electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) were used to evaluate cortical responses to a low-level visual task. Evidence for a *weaker visual cortex response* (in EEG) and *reduced inhibition of auditory association areas* (in EEG and fNIRS) in the CI children with language delays suggests that cross-modal reorganization can be maladaptive and does not necessarily strengthen the dominant visual sense.

## INTRODUCTION

In response to a sensory deprivation, the brain reorganizes itself to strengthen another sense – vision, hearing, or somatosensory processing have been most explored – and the degree of reorganization will increase corresponding to the onset and duration of deprivation (Lazzouni and Lepore, 2014). For example, following congenital blindness, the occipital cortex may be recruited for Braille reading, to discriminate vibrotactile stimuli (Liu et al., 2007; Ptito et al., 2009), localize sounds (Collignon et al., 2009), process spoken language (Bedny et al., 2015) and support verbal memory (Occelli et al., 2017). Following congenital deafness, the auditory cortex may be recruited for sign language (Lambertz et al., 2005), for specific visual tasks or movements (Finney et al., 2001; Corina and Singleton, 2009; Lomber et al., 2010), and to process vibrotactile stimuli (Auer et al., 2007). All these examples of *cross-modal plasticity* are evidence for the incredible capacity of the brain to adapt to any environment over a prolonged period of time, particularly early in life.

Although not always explicitly stated, the term ‘adaptation’ is often presented in a positive light: a key feature of the cross-modal changes aforementioned is that the brain *compensates* for the deprivation of one sense with *enhanced abilities* in another. But this view somewhat conflicts with our current understanding of brain development where interconnected networks develop and specialize in tandem. This has been formulated by the Interactive Specialization framework (Johnson, 2011). Especially for complex functions such as language processing which is inherently multimodal and integrative (Friederici and Gierhan, 2013), the auditory and visual systems need to support each other rather than compete. From this perspective, one might expect the brain to *suffer* from the deprivation of one sense with *poorer abilities* in another. To draw a simple analogy, think of a table with a missing leg: aside from being fragile, it might also put extra strain on the remaining legs making them weaker, not stronger.

One key in understanding why networks specialize in a certain way is to figure out at what time they seem to be particularly prone to experiential influences, i.e. sensitive periods (Hooks and Chen, 2007; Voss et al., 2017). For example, around one year of age, there is a shift from children looking preferentially at the

eyes of a speaker to looking at their mouth (Lewkowicz and Hansen-Tift, 2012). Around the same time, a window for discrimination of native vs non-native speech sounds closes (Werker and Hensch, 2015). If both are supposed to help each other to build the foundations of future lip-reading skills, then auditory deprivation might not necessarily facilitate lip-reading. This is where children with cochlear implants (CI) happen to be a population of choice in this scientific endeavor, because they allow for the environment to change suddenly (e.g. the world no longer being silent) as a particular window of plasticity closes.

Today, in many cases of congenital deafness, children may receive a CI as early as one year of age (occasionally even earlier) and their hearing recovers impressively. But there is a large variability in outcomes which remains unexplained. Typically, multi-factorial models account for 50% of the variance (Sarant et al., 2001; Geers et al., 2003, and substantially less in adults e.g. Blamey et al., 2013; Lazard et al., 2012), using a combination of personal characteristics (cognitive skills, non-verbal intelligence, inherent language aptitudes), device parameters (electrode array, quality of mapping, and electric dynamic range), and communication mode (Geers et al., 2003; Dettman et al., 2013; Ambrose et al., 2015; Busch et al., 2019; Wolfe et al., 2021). We strongly suspect that the status of the auditory nerve and auditory brain (Feng et al., 2018; Sharma et al., 2002) would be additional factors to further explain why a given child derives much benefit from their device while another is not, despite both being implanted at a young age (Geers et al., 2016, 2019).

Some aspects of brain reorganization have been explored in CI users. A series of electroencephalography (EEG) studies demonstrated activity in the auditory cortex of CI adults elicited by a visual task (Doucet et al., 2006; Buckley and Tobey, 2011; Sandmann et al., 2012; Kim et al., 2016). These cross-modal visual evoked potentials (VEPs) were viewed as *undesirable* because their size was (often) inversely related to speech recognition skills. Comparatively, fewer studies exist in CI children whose findings support the maladaptive nature of cross-modal changes (Sharma et al., 2005, 2007, 2009, 2015; Cartocci et al., 2021). On the other hand, cross-modal changes have also been associated with *positive outcomes*. Using positron emission tomography (PET), Giraud et al. (2001) found increased visual cortex response to sounds over time after implantation with responses tuned to meaningful sounds (i.e. words more than vowels); and Strelnikov et al. (2013) found a desirable activation of the visual cortex (to visual speech) for later auditory recovery (both studies in post-lingually deafened individuals). Similarly, using functional near-infrared spectroscopy (fNIRS), studies have found a positive association between visual speech and post-implantation activation of the bilateral superior temporal gyrus (Anderson et al., 2017a in post-lingually deafened CI adults; and Mushtaq et al., 2020 in pre-lingually deafened CI children). These cortical changes are clearly *adaptive* when considering the large benefit that lip-reading provides to support communication, including in pediatric users (Tyler et al., 1997). To some degree, this apparent dichotomy has been driven by the choice of neuroimaging technique. Weaker responses in an event-related potential (ERP) paradigm have traditionally been interpreted as poorer encoding, but might on the contrary be a sign of efficiency if one considers adaptation induced by repeated stimuli. If so, the interpretation may be more in line with a hemodynamic technique (Chen et al., 2017). This is the sort of methodological debate that motivated us to combine EEG and fNIRS here to get a comprehensive picture of cross-modal reorganization in this population.

To summarize, CI users exhibit reorganization in both auditory and visual cortices (Chen et al., 2016), but whether these changes are adaptive or maladaptive remains debated. Beyond methodological discrepancies, we suspect that the answer has to do with the pressure that language exerts on the connectivity between the visual and auditory cortices. Using two groups of CI children (all implanted before 4 years of age), some with age-appropriate language skills and some with delays, as well as normally-hearing (NH) controls, we investigated the response of the visual and auditory cortices to a low-level visual task. Compensatory cross-modal changes would predict 1) a recruitment of the auditory cortex and 2) a stronger visual response, which would be beneficial in the long-term to CI children's language outcomes. Deleterious cross-modal changes would predict 1) a recruitment of the auditory cortex but 2) a weaker visual response, which would be detrimental to CI children's language outcomes.

## RESULTS

**EEG findings:** The repetitive presentation of the checkerboard elicited a large response in the occipital lobe and a weak deactivation of the superior temporal cortices (Figure 1). The group-averaged occipital waveforms had a large initial peak occurring around 120-130 ms, representing a *pattern-onset VEP* from the grey background that preceded every visual event, followed by more modest peaks occurring roughly at 225, 350, 475, and 600 ms. The 125-ms periodicity matched the rotation of the checkerboard, suggesting that these peaks were *pattern-reversal VEPs*, occurring roughly 100 ms after each reversal.

[FIGURE 1 and 2 ABOUT HERE]

**1. Visual cortex:** The first peak of the occipital response (i.e. pattern-onset VEP) was the most striking feature differentiating the groups. Its corresponding source was unexpectedly biased towards the left side (Figure 2, left panel). We also examined the topographical maps for the later peaks (i.e. pattern-reversal VEPs), individually or averaged together, but these analyses failed to find group differences (Appendix A). So, we focus here on the first peak. The LME analysis revealed a main effect of group on P1 amplitude [ $c^2(2) = 11.7, p = 0.003$ ], driven by smaller peaks for the LL than the HL group ( $p = 0.009$ ). Peaks were on average 7.6, 13.9, and 11.5  $\mu\text{V}$ , respectively in LL, HL, and NH groups (bottom-left, Figure 1). There was also a main effect of chronological age [ $c^2(1) = 15.4, p < 0.001$ ], with a linear trend showing a reduction of 11.4  $\mu\text{V}$  in a decade (explaining 23% of the variance). However, there was no interaction between age and group [ $c^2(2) = 4.3, p = 0.117$ ]. For P1 latency (not shown) which averaged at 123.9 ms, there was neither a main effect of group [ $c^2(2) = 4.4, p = 0.110$ ], nor a main effect of chronological age [ $c^2(1) = 0.3, p = 0.620$ ], without interaction [ $c^2(2) = 2.2, p = 0.338$ ]. Among children with CIs, we found that both amplitude and latency of the pattern-onset VEP decreased with age at implantation [ $r^2 = 0.11, p = 0.018$  and  $r^2 = 0.08, p = 0.044$ ]. Finally, amplitude (but not latency) positively correlated with the CELF score [ $r^2 = 0.14, p < 0.001$ ] in line with group differences.

**2. Auditory cortex:** At the same time as the pattern-onset VEP observed over the visual cortex, an independent source was revealed by the source localization analysis over the STG/MTG (Figure 2, right panel). This was a key finding: the reverse waveforms recorded over temporal electrodes were not simply

a by-product of the visual cortex response but had genuinely a cross-modal origin. Moreover, the LME analysis conducted on the average potential revealed a main effect of group [ $c^2(2) = 6.2, p = 0.046$ ], driven by stronger inhibition for the HL and NH groups compared to LL group [ $p < 0.040$ ]. The average potential amplitudes were -0.38, -0.90, and -0.97  $\mu\text{V}$ , respectively in LL, HL, and NH groups (bottom-right, Figure 1). There was also a main effect of chronological age [ $c^2(1) = 19.4, p < 0.001$ ], without interaction [ $c^2(2) = 1.5, p = 0.483$ ]. The negative potentials were weaker (i.e. less negative) in older children, with an estimated slope of 1.6  $\mu\text{V}$  per decade (explaining 26% of the variance). Among children with CIs, this deactivation was progressively lost with later implantation [ $r^2 = 0.10, p = 0.023$ ] and stronger for the children with better language outcomes [ $r^2 = 0.10, p = 0.006$ ] (most-right bottom, Figure 1).

**3. Summary of EEG findings:** As expected, the checkerboard task elicited strong activity in the visual cortex of all children, along with a modest deactivation of auditory association areas. The occipital response was arguably complex, with each rotation of the checkerboard eliciting its own visual event resulting in additional peaks in the waveform spaced every 125 ms. Yet, this complexity could be broken down by isolating the first peak as a pattern-onset VEP dependent on group, while later peaks were several instantiations of pattern-reversal VEPs which were less group-dependent (Appendix A). The weaker visual cortex response exhibited by the LL group provides support *against the hypothesis of compensatory changes*. In middle/superior temporal cortices, potentials were negative at the scalp and had an origin separate from the visual cortex, suggesting that this region was disengaged (see Appendix D for a further discussion on this inhibition). But critically, it was less so in the LL group, again providing support *against the hypothesis of compensatory changes*.

**fNIRS findings:** The checkerboard elicited a strong occipital response, revealed by a significant increase in HbO and a significant decrease in HbR in channels located on occipital regions (Figure 3). Apart from visual areas, the rest of the brain showed either little change or was deactivated. Frontal and parietal regions were uncorrelated with the occipital activity but both motor and temporal regions were anti-correlated with the occipital activity. The deactivation of the superior and middle temporal cortices was especially evident in NH children, much less so in CI children.

**1. Visual cortex:** The ANOVA did not support a main effect of group [ $F(2,72) = 0.6, p = 0.556$  for HbO;  $F(2,72) = 1.6, p = 0.216$  for HbR]. Individual values of HbO-HbR did not depend on chronological age [ $p = 0.339$ ] and did not relate to language outcomes [ $p = 0.253$ ]. For children with CIs, these values did not relate to age at implantation [ $p = 0.392$ ].

**2. Auditory association areas:** There was a main effect of group over STG driven by changes in HbO [ $F(2,72) = 5.1, p = 0.009$ ] but not in HbR [ $F(2,72) = 0.7, p = 0.507$ ]. Similarly, there was a main effect of group over MTG driven by changes in HbO [ $F(2,72) = 3.8, p = 0.028$ ] but not in HbR [ $F(2,72) = 0.3, p = 0.769$ ]. Post-hoc comparisons clarified that the group effect (on HbO) was driven by a stronger deactivation in the NH group compared to both LL and HL groups [ $p < 0.030$ ], which did not differ from

each other. Chronological age did have a role over STG [ $r^2 = 0.11$ ,  $p = 0.003$ ] (but not over MTG [ $r^2 = 0.03$ ,  $p = 0.144$ ]) suggesting that younger children were more prone to deactivate auditory regions than older children. This deactivation did not relate to age at implantation [ $p = 0.664$  and  $p = 0.889$ , respectively in STG and MTG], but tended to be associated with better CELF score [ $p = 0.086$  over STG and  $p = 0.041$  over MTG] (bottom-right, Figure 4).

**3. Summary of fNIRS findings:** As expected, the visual task generated strong occipital activity in both HbO and HbR signals. Unfortunately, group differences were not significant over V1/V2 (but could perhaps be appreciated in terms of spread – Appendix B). The same applied to V3 or the fusiform gyrus (not shown) where the response was reduced in all groups. So, the visual ROI in this task was not helpful in addressing our competing hypotheses, but the auditory ROI was. NH children consistently deactivated the STG/MTG while this trait was largely absent in children with CIs but would have been desirable given its association to language outcomes.

## DISCUSSION

The goal of this study was to explore phenomena of cross-modal plasticity by taking advantage of a population whose brain had gone through a first round of plastic changes under auditory deprivation, and a later round of plastic changes once their hearing had recovered through electrical stimulation of their auditory nerve. If some aspects of the visual and auditory networks relied on sensitive periods for spoken language, and that some of them would be missed due to auditory deprivation, then one might expect both the auditory or visual cortices to take on a differential developmental trajectory than for NH children. But the effect could be mitigated by inherent language aptitudes (Ortmann et al., 2013) if indeed language was the driver of the interactive specialization of the visual and auditory networks (Johnson et al., 2011).

More specifically, we suspected that children with CI would exhibit signs of cross-modal recruitment of auditory cortex by vision, i.e. left-over marks from the first round of plastic changes which had not completely reverted since CI experience. Both EEG and fNIRS data did provide some support for it as (at least some) children with CIs *failed to inhibit auditory areas* while this inhibition was a clear trait exhibited by NH controls. The interesting question is whether these cross-modal changes are adaptive or maladaptive. Our data support the latter on the basis that this inhibition of MTG/STG (the inverse coupling between visual and auditory systems) related to better language outcomes (bottom-right of Figure 1 and 4). So, lacking it is not a good sign. Evidently, the brain cannot know what the world will be like tomorrow (e.g. predicting that it will cease to be silent). So, these changes are not detrimental per se but only because they specialized for an environment that is now outdated.

As for the visual cortex, the present data calls for caution when interpreting the pattern of responses, and bearing in mind the technique with which observations were made. In EEG data, other than age effects which presumably had physiological roots (Appendix C), a declining response by the visual cortex may be the result of adaptation (Chen et al., 2017). Whether or not it is a sign of *efficiency* is doubtful. Here,

visual adaptation would be revealed by a high first peak followed by rapidly decreasing peaks. We did observe the highest pattern-onset VEPs in HL children, but negligible difference in subsequent peaks (Appendix A). Even if we were to interpret this finding as children in the HL group having a more efficient visual system, then by the same reasoning, children in the LL group would have the least efficient visual system. Yet, the LL group had (on average) longer periods of auditory deprivation, so we have to conclude that their brain did not promote vision. Similarly for the hemodynamic results, if the response magnitude reflected a form of mental energy consumption (which would be best kept as low as possible in a low-level task devoid of communication purpose), then both CI groups have not figured out an efficient way to save cognitive resources. Thus, the fNIRS data do not agree either on an interpretation based on efficiency or resource allocation. Paradoxical as it may be, auditory deprivation did not result in a more efficient visual system, quite the contrary and especially for children with poor language outcomes.

Similar paradoxes and inconsistencies have been raised in the literature, and could partly be due to the profile of CI users. Weaker visual responses have been reported in post-lingually deafened CI adults (Sandmann et al., 2012; Kim et al., 2016; Chen et al., 2017), while stronger visual responses have been found in pre-lingually deafened CI children (Campbell and Sharma, 2016). But even within a population that shares much similarity, results are inconsistent. In the study by Campbell and Sharma (2016), the 5-15 year old children were comparable to the present LL group (given their age at implantation and speech scores) and they obtained earlier and larger VEPs compared to NH children, while we observed the contrary. Of course, there are methodological differences, as their visual stimulation could have engaged more connections to the rest of the brain while ours was perhaps more prone to adaptation effects. These methodological differences could explain why plastic changes appear fundamentally distinct: targeting the right temporal cortex (Campbell and Sharma, 2016) or posterior parietal regions but not the auditory cortex (Hauthal et al. 2014, in deaf adults without CI). A more complex network, including prefrontal and parietal regions, was also observed by Giraud et al. (2000) in post-lingually deafened CI users. We did not see clear evidence that parietal regions were recruited here, and we cannot speak about the likelihood of enhanced multisensory integration. But what seems to emerge is that the visual cortex response is difficult to interpret on its own (being highly task-dependent), whereas the response captured over STG/MTG to visual stimulation is a reliable indicator of maladaptive plastic changes.

### **Localized versus spread activity**

Pattern-onset VEPs are generally known to be *larger in amplitude* than pattern-reversal VEPs and *their latency differs* about 125 versus 100 ms, respectively (Shagass et al., 1976; Ossenblok et al., 1992; Hoffmann et al., 2003), although this depends somewhat on spatial and temporal frequencies (Parry et al., 1999). Here, we replicated this difference in amplitude (about 11 versus 6  $\mu\text{V}$ ) and average latencies of 124 versus 98 ms. Interestingly, the two visual stimulations are thought to activate different neural generators. Pattern-reversal VEPs are supposedly generated from V1 exclusively (Di Russo et al., 2005), whereas pattern-onset VEPs have multifocal generators, some of which at V2 or higher visual areas (Maier et al., 1987; Ossenblok et al., 1991; Hoffmann et al., 2003). The fact that we observed group differences in pattern-onset but not in pattern-reversal suggests that activity in V1 was similar across



groups, but *weaker* in the LL group in *peripheral* visual areas. This was corroborated to some degree with the fNIRS data: the LL group's response faded in amplitude from the single channel over V1 to the periphery of the visual cortex while it was more maintained in HL and NH children (Appendix B). This narrowing of the cortical activation in a low-level task is a feature predicted by the Interactive Specialization framework (Johnson, 2011) and one that would deserve further exploration. But an important consequence of this differential spread in activation is that whether one concludes of enhanced or impaired response to a given stimulation is evidently dependent on the size of the ROI chosen (in addition to the task dependency aforementioned).

## Clinical significance

The idea that visual language reinforces cross-modal plasticity thereby compromising the functions of the auditory cortex has been questioned. In a review of this literature, Lyness et al. (2013) argued that there is in fact no evidence to link the use of visual language to poorer CI outcomes. Instead, they pointed towards the detrimental role of *language deprivation* during sensitive periods. This debate has major implications because sign language is often discouraged in rehabilitation of children with CIs. A similar conclusion was reached by Mushtaq et al. (2020) when observing through fNIRS that CI children displayed similar responses to auditory speech as NH children in the temporal cortex and even larger responses to visual speech than NH children. Thus, they recommended *encouraging the use of visual language* in this pediatric population. The current findings do not allow us to comment on this debate with any degree of certainty. Our current position is that the LL group exhibited a form of uncoupling between auditory and visual functions, which was generally detrimental to language. But further work is needed to better understand why recruitment of auditory cortex during a visual task is (most often) *maladaptive* while recruitment of visual cortex during an auditory task is (most often) *adaptive*, and the conditions in which this dichotomy may be found (Stropahl et al., 2016; Anderson et al., 2017b; Glennon et al., 2020).

## CONCLUSION

To this day, some children with CIs struggle at school, despite early implantation and continuous rehabilitation efforts (Geers et al., 2016, 2019). Here, we provided converging evidence - using non-simultaneous EEG and fNIRS - that one reason for these on-going difficulties is that the brain of these children has organized itself in a way that is not favorable to language development. These changes, surprisingly, did not seem to promote visual information, at least not in response to a checkerboard. The most consistent marker observed across the two techniques was the lack of inhibition of superior/middle temporal cortices. Not seeing this inverse coupling between visual and auditory functions may be an indication that the brain of some (but not all) children with CIs is not tuned optimally to integrate linguistic stimuli which are intrinsically audio-visual.

## GENERAL METHODS

**Participants:** Seventy-five children between the ages of 7 to 18 participated. Twenty-five children with normal hearing and typical language development served as a control population (group NH). Fifty children had CIs without comorbidity, communicating through spoken language primarily. Outcomes of language were used to split the group with low language (LL) from the group with high language (HL) aptitudes. This was evaluated through the Clinical Evaluation of Language Fundamentals - fifth edition (Wiig et al., 2013) standardized at a score of 100. Children in the LL group had CELF scores below one standard deviation (<85) while children in the HL group had CELF scores above average (>100). All implanted children were properly fitted (aided thresholds of 20-30 dB). Children in the LL group were fitted with a hearing aid and then implanted *at a later age* than children in group HL. This difference might seem small (on average, about 17 vs. 7 months for hearing aid fitting, and 27 vs. 20 months for first implantation), but at such young ages, we know that this has repercussions for the development of speech recognition skills (Ching et al., 2018; Dettman et al., 2016; Geers et al., 2019; Leigh et al., 2016; Tajudeen et al., 2010) and we confirmed these repercussions with audiological outcomes in a previous study (Wolfe et al., 2021). Forty-five children were bilaterally implanted, all 26 from the HL group and 19 in the LL group. Second implantation occurred about 16-17 months after the first implant, and the time interval between first and second CI did not differ between the two groups. Finally, the three groups did not differ in sex [chi-Square test;  $\chi^2(2, N = 75) < 0.1, p = 0.987$ ] but did differ in chronological age: children in the LL group were the oldest ( $13.9 \pm 2.6$  years), followed by the NH group ( $12.6 \pm 3.1$  years), and the HL group ( $11.5 \pm 2.8$  years). Note that this difference was not intended, but if anything it ought to confer some maturational advantage to the LL compared to the HL group.

**Stimuli:** Children watched a single type of stimuli: a circular checkerboard (Hoffmann et al., 2003), made of 24 alternated patterns of black and white areas over 360 degrees and 6 concentric rings. This checkerboard rotated every 125 ms to its mirror image. For EEG data acquisition, the checkerboard was presented for 500 ms, followed by a 1000-ms gray screen, and repeated 200 times, resulting in a 5-minute task. This stimulation was designed to elicit two types of VEP: one in response to a *pattern onset* as the checkerboard appeared from a gray background every 1500 ms, and the other in response to a *pattern reversal* as the checkerboard rotated. This choice increased our chance of observing different aspects of visual processing, more or less prone to adaptation (Chen et al., 2017) and inducing different spread of activation (Tobimatsu and Celesia, 2006). For fNIRS data acquisition, the checkerboard was presented for 15 seconds (still rotating at 8 Hz) followed by a 15-second rest, and repeated 10 times. Again, this resulted in a 5-minute task. All tasks were generated using *PsychoPy* and included triggers at the onset of each visual event.

**Equipment:** All data was acquired at *Hearts for Hearing* (<https://heartsforhearing.org/>) in Oklahoma City. EEG was recorded using a high-density 128 electrode sensor array net placed on the scalp using *Electrical Geodesics Inc* (EGI) system (MagstimEGI, Oregon, USA). The impedance was kept under 10 k $\Omega$  throughout the recording. The reference electrode was located at Cz. The raw data was sampled at 1000 Hz (EGI net amps 300 system) and stored for offline analysis. Continuous fNIRS was recorded using 39 LED sources and 31 detectors from the NIRSout system developed by *NIRx Medical Technologies* (LLC,

USA), whose theoretical montage was shown in Alemi et al. (2023). Each source emitted near-infrared light at two wavelengths 760 and 850 nm. An *EasyCap* (EASYCAP GmbH, Germany) was used to hold the sources and detectors, and their position was registered with three fiducials (nasion and left/right pre-auricular point) and later digitized using the *FieldTrip* toolbox (Oostenveld et al., 2011). There were 122 channels in total whose source-detector distance was on average 29.9 mm ( $\pm 6.5$  mm). No short channel was present in the montage (removal of systemic components was performed with PCA). Before starting the recording, the experimenters checked the automatic gains for all channels and attempted to move hair out of the way to optimize skin-to-optode contact. These gains were not changed once the recording had started.

**Protocol:** The rationale for this research was explained to each child and their respective parents, and the entire protocol was described, after which parents and children provided informed consent. A battery of audiological tests along with language assessments were collected in addition to information pertaining to the implant and the progression of hearing loss. Children were then invited to sit still in a chair placed one meter in front of a laptop on which the checkerboards were displayed (similar to Figure 2 in Koirala et al., 2023 for EEG; and Figure 1 in Alemi et al., 2023 for fNIRS). The experimenters (co-authors J.W., S.N., J.M., L.H., W.T.) placed proper caps after measuring the child's head size. The data from the two imaging techniques were acquired sequentially, with counterbalanced order. Several other tasks were conducted using the same techniques in each child on the same day: a low-level auditory task (Deroche et al., 2023), a motor task (Alemi et al., 2023), a phonological task (spoken/written words and sudo-words), an audio-visual integration task (McGurk), emotional processing (a 10-min child-friendly video from the movie *Despicable Me*), and a 7-min resting-state recording (Koirala et al., 2023). As the entire protocol for each technique was substantial, they were conducted at different times with a large break in between. Each participant was compensated financially for their participation and the experiment was approved by the Western Institutional Review Board (reference #20190882).

**EEG data analysis:** The recorded brain activity was analyzed offline using *EEGLAB* (Delorme and Makeig, 2004) and its "erplab" plugin running under the *MATLAB* (Mathworks Inc., Massachusetts, USA) environment. The 7-min resting-state recording and the 5-min checkerboard task were concatenated, the former being present only to help the Artifact Subspace Reconstruction (ASR) method (Kothe and Makeig, 2008; Chang et al., 2018) spot bad data periods. The events were adjusted by 50 ms to compensate for the delay between triggers sent to *NetStation* software relative to the occurrence of visual events. The data were re-referenced to the average of all 128 channels, band-pass filtered between 0.1 and 30 Hz with a 2<sup>nd</sup> order Butterworth filter, and resampled at 256 Hz. Next, the *clean\_rawdata* plugin that implemented the ASR method was used to correct bad data periods, and additional bad data periods were removed if they exceeded 7 standard deviations (with at most 25% out-of-bound channels). There remained on average  $163.9 \pm 29.6$  trials with a minimum of 83 and a maximum of 200 trials. This represented 82% of the initial data, and the statistical analyses on the number of trials excluded did not show significant difference between groups [ $F(2,72) = 3.1, p = 0.053$ ]. A similar analysis was conducted for channel rejection: there were on average  $119.1 \pm 4.6$  remaining channels with a minimum of 105 and a maximum

of 128, representing 93% of the initial 128 channels, also with no group difference [ $F(2,72) = 0.4, p = 0.645$ ].

The data were epoched from -200 to +1300 ms relative to the onset of the checkerboard, correcting for the baseline (-200 to 0 ms), and passed through an independent component analysis (ICA) using the extended option of the *runica* command and fed to the *ADJUST* plugin (Mognon et al., 2011; Chaumon et al., 2015). This algorithm did not favor nor penalize any particular group [ $F(2,72) = 2.6, p = 0.078$ ]. There were on average  $15.5 \pm 6.6$  independent components removed:  $1.3 \pm 2.8$  were eye blinks,  $4.5 \pm 3.1$  horizontal eye movements,  $4.0 \pm 3.1$  vertical eye movements, and  $8.9 \pm 5.2$  generic discontinuities. Finally, all missing channels were spherically interpolated, and all epochs were averaged for each subject and each channel. The analysis was focused on two ROIs that were selected using a set of electrodes to isolate the activity of the visual cortex and auditory cortex. For visual cortex, a group of 5 electrodes surrounding Oz, namely E75, E70, E83, E74, and E82 were selected according to the *EGI* nomenclature. For auditory cortex, the bilateral superior temporal cortices were selected from E41, E46, E40, E45 on the left side and E102, E103, E109, E108 on the right side. The occipital lobe response consisted of several peaks, each extracted within a  $\pm 50$  ms window centered around 130, 225, 350, 475, and 600 ms. The negative deflection in the waveform recorded over the superior temporal cortices was less systematic: rather than peak extraction, we averaged the potential over the presentation of the checkerboard from 0 to 500 ms.

A linear mixed effect (LME) analysis (Matlab's *fitlme* function – Pinheiro and Bates, 1996) was conducted on the dependent variable (e.g. amplitude or latency of a given peak) with two fixed factors: group and chronological age. It was necessary to include age because the waveforms measured in older children tended to be reduced (Appendix C). For the same reason, all models included random intercepts by head size and by sex (both of which known to affect VEPs, Sharma et al., 2015; Dion et al., 2015). Each main effect and interaction was tested by likelihood ratio tests progressively adding fixed terms to the final formula:  $DV \sim \text{group} * \text{age} + (1 | \text{headsize}) + (1 | \text{sex})$ . Finally, linear regressions were systematically conducted for age at first implantation and CELF score. Furthermore, we wanted to determine that the ERP waveforms elicited by the checkerboard and recorded from scalp electrodes over auditory areas had indeed an origin in STG/MTG, so we performed a source analysis (Michel et al., 2004; Muthuraman et al., 2018; Michel and Brunet, 2019). We used the first ERP peak for each subject, separately for occipital and temporal regions, and separately for the three groups. ERP source analyses were conducted using the minimum norm estimation for time-locked ERPs (Dale et al., 2000; Ou et al., 2009; Jensen and Hesse, 2010). The forward problem was solved using the volume conduction model using template MRI (Fuchs et al., 2002; Hallez et al., 2007; Vorwerk et al., 2014) and the inverse solution with the minimum norm (Grech et al., 2008).

**fNIRS data analysis:** The fNIRS data were analyzed using the *Brain AnalyzIR Toolbox* (Santosa et al., 2018). Step 1: the entire recording was trimmed 5 seconds before the first trigger and 5 seconds after the last trigger so that the selection of good/bad channels was based exclusively on the signal quality during the task. Step 2: oversaturated channels were replaced with high variance noise. Step 3: bad channels were flagged if their standard deviation over the trimmed signals (averaged over the two wavelengths)

exceeded 15%. There were on average 18.4, 15.9, and 6.7 bad channels (out of 122) in group LL, HL, and NH respectively, and this main effect of group was significant [ $F(2,72) = 6.6, p = 0.002$ ] driven by fewer rejections in the NH group compared to LL and HL groups [ $p = 0.003$  and  $p = 0.021$ , respectively], while LL and HL did not differ [ $p = 0.736$ ]. In other words, NH children exhibited cleaner signals than children with CIs and we conjectured that this was related to the presence of the magnetic coil reducing the scalp-to-optode contact in some areas. All flagged channels were linearly interpolated from adjacent good channels. Step 4: signals were converted to optical density (Huppert et al., 2009). Step 5: motion artifacts were corrected using Temporal Derivative Distribution Repair (TDDR) on the data which was first projected onto a PCA space before projecting back to the optical density space (Fishburn et al., 2019). Step 6: optical density signals were converted into changes in oxyhemoglobin (HbO) and deoxyhemoglobin (HbR) concentration using the modified Beer-Lambert Law (based on extinction coefficients from Jacques, 2013) and based on source-detector distances calculated from the digitized montage specific to each child. The differential pathlength factors were set at 7.25 and 6.38 for the 760 and 850 nm wavelength respectively, and the absorption coefficients ( $\mu_a, \text{mm}^{-1} \cdot \text{M}^{-1}$ ) were the following:  $\mu_a(\text{HbO}, 760 \text{ nm}) = 134.9$ ,  $\mu_a(\text{HbO}, 850 \text{ nm}) = 243.6$ ;  $\mu_a(\text{HbR}, 760 \text{ nm}) = 356.6$ , and  $\mu_a(\text{HbR}, 850 \text{ nm}) = 159.1$ , implemented in the toolbox. Step 7: Hb signals were band-pass filtered between 0.01 and 0.25 Hz to limit low-frequency drift and cardiac oscillations. Step 8: Hb signals were passed through a PCA and the first component was systematically removed. Screening through the responses of each child successively, we found it to be a more efficient way to remove the systemic component of the signals than a spatial filtering method (Zhang et al., 2016).

The subject-level statistics was performed by the *AR\_IRLS()* function of the toolbox, using the default properties of the canonical hemodynamic response function (Barker et al., 2013; Huppert, 2016). Group-level statistics followed a mixed effect approach defined as:  $\text{beta} \sim -1 + \text{cond:Group} + (1|\text{Subject})$ . The statistical maps in 3D were projected on the average digitized montage and ROIs were isolated. The Talairach atlas was used to label brain regions for each channel, based on the probability that a given channel overlapped with a known cortical region (along the same reasoning as *fOLD* toolbox, Zimeo Morais et al., 2018). A total of 20 channels overlapped with the primary visual cortex (V1) and visual association cortex (V2) in different proportions between 28.4% and 99.4% resulting in a weighted average for the visual ROI. The second ROI was selected to overlay with the auditory cortex. A total of 18 channels were partially overlapping with the superior temporal gyrus (STG, Brodmann area 22) with proportions varying from 20.7% to 32.1%, and 26 channels were overlapping with the middle temporal gyrus (MTG, Brodmann area 21) with proportions varying from 21.6% to 69.1%. Group averages of HbO and HbR waveforms were calculated after baseline correction (using 5-sec prior to the checkerboard onset) for visualization purposes; but the GLM analysis was entirely conducted on the weighted beta values mentioned above. Analysis of variance with one between-subject factor (groups LL, HL, and NH) was conducted in each ROI on the beta values for HbO, HbR. Using the difference HbO-HbR (to limit the inflation of type-1 error), regression analyses systematically investigated the effect of chronological age, age at implantation, and CELF score.

# Declarations

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## Author contributions

MD, JW, and VG developed the rationale and conceptualization of the research program. MD coded the experimental interface, analyzed the data, and wrote up the core of the manuscript. JW, SN, JM, LH, WT collected all the EEG and fNIRS recordings. CW, AB, SM, and ES helped with subject recruitment. JG helped with fNIRS data analysis, and NK and MM helped with EEG source analysis. All authors contributed to manuscript editing.

## Declaration of conflicting interests

The authors have declared that no competing interests exist. MD received funding from industrial partners *Oticon Medical* and *Med-El*, but for unrelated work. JW is a member of the Audiology Advisory Boards of *Advanced Bionics* and *Cochlear*, the manufacturers of the cochlear implants used by the participants in this study, but no funding from these industrial partners was received for this particular study.

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## Figures

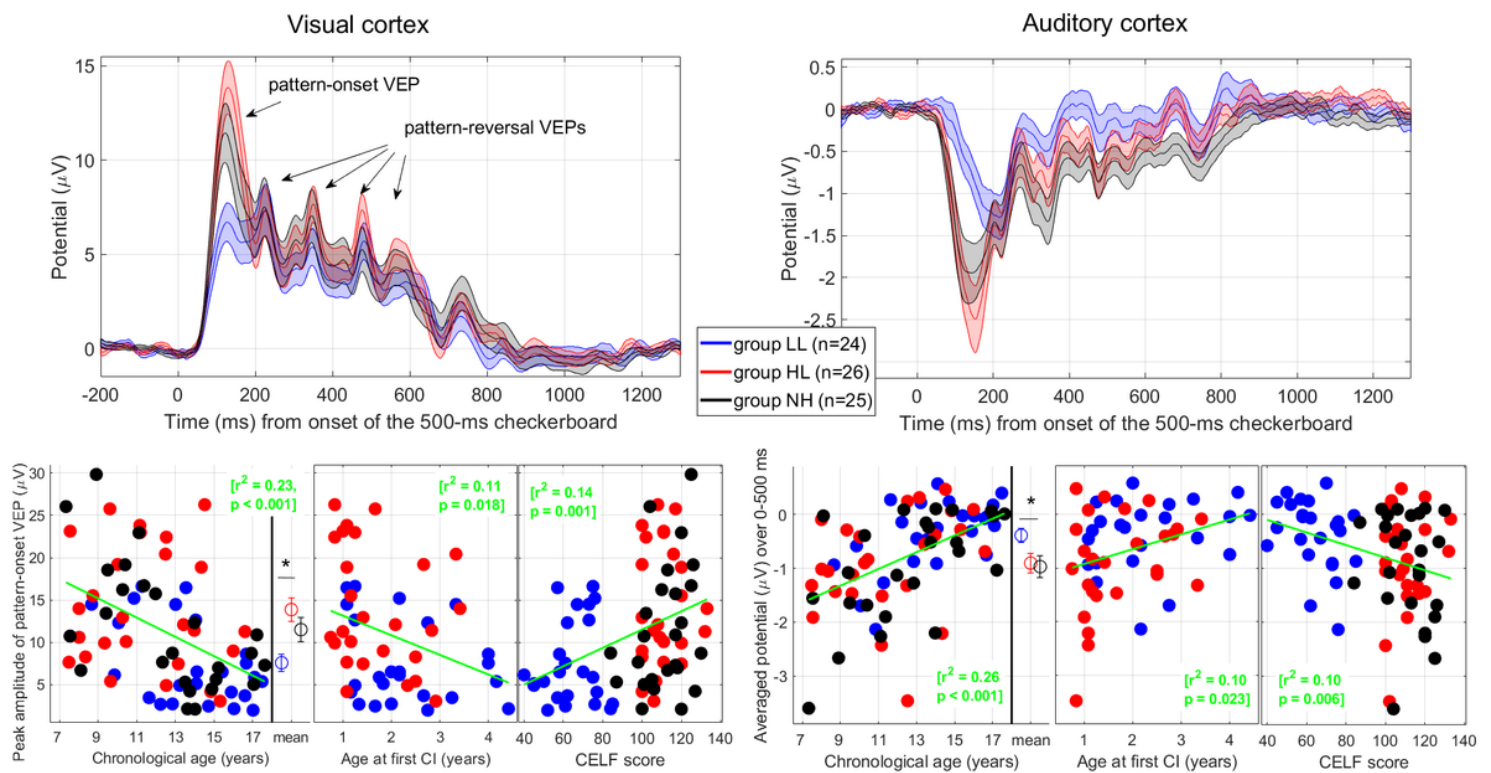


Figure 1

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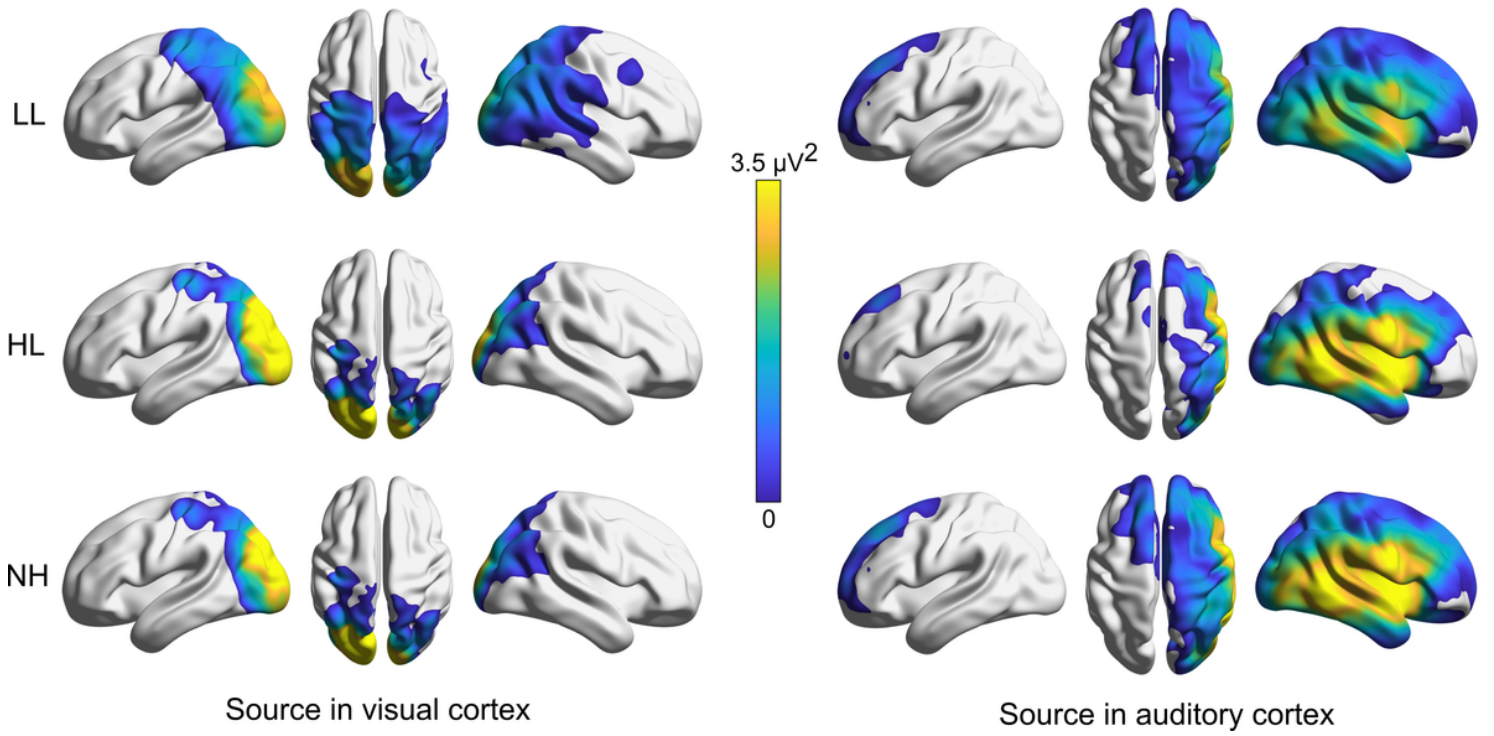


Figure 2

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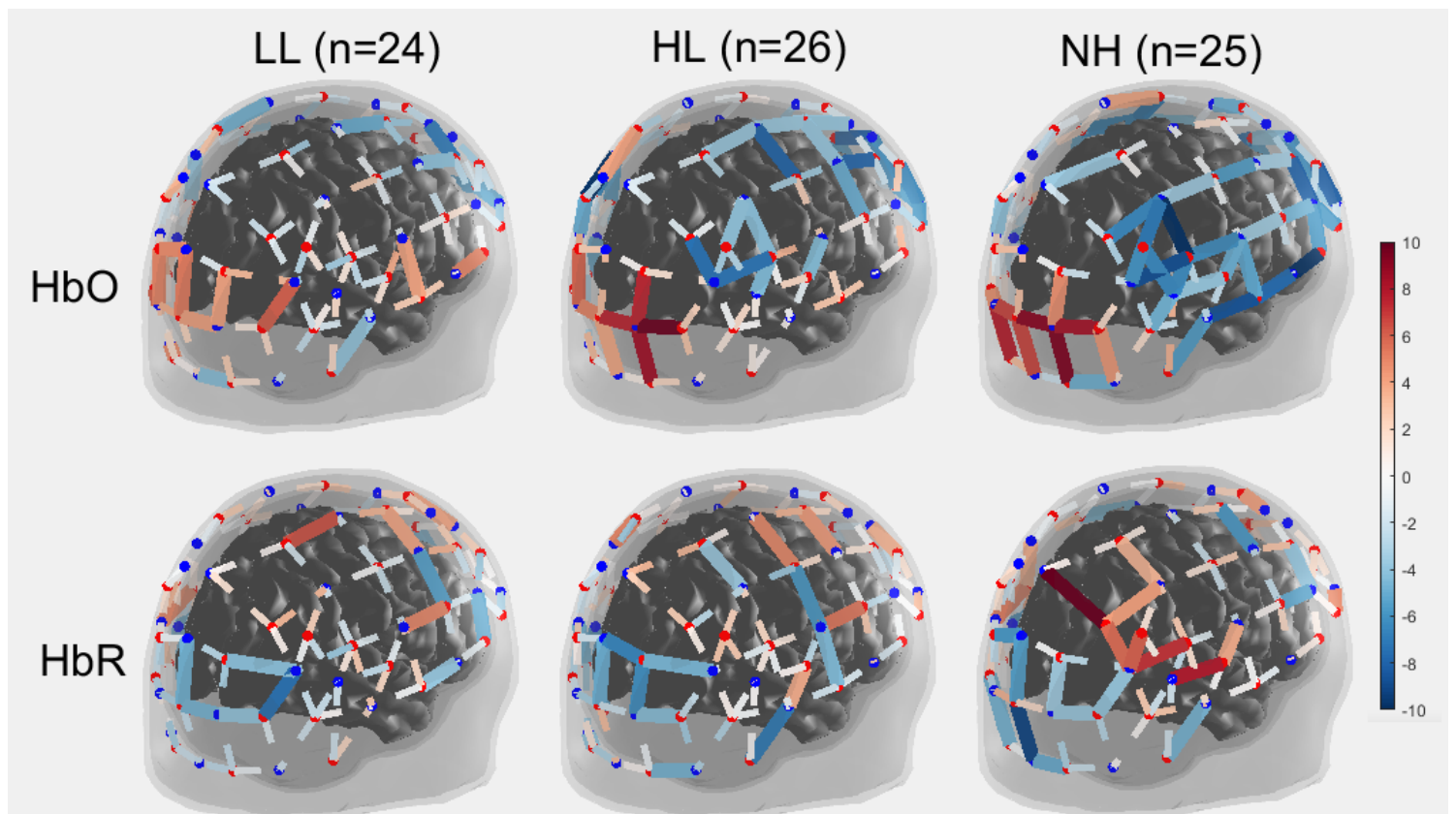


Figure 3



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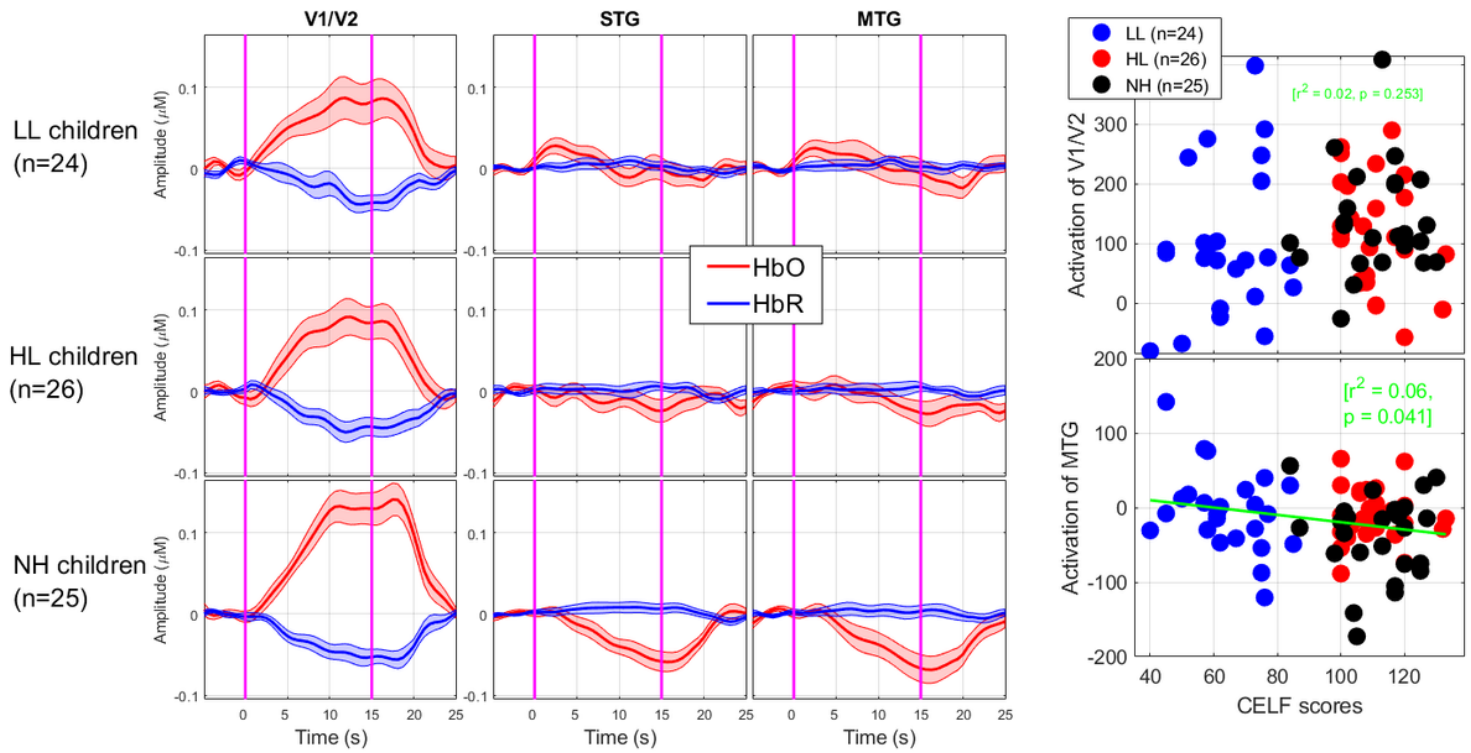


Figure 4

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