Visual processing recruits the auditory cortices in prelingually deaf children and influences cochlear implant outcomes

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Abstract

Objective: Although visual processing recruitment of the auditory cortices has been reported previously in prelingually deaf children who have a rapidly developing brain and no auditory processing, the visual processing recruitment of auditory cortices might be different in processing different visual stimuli and may affect cochlear implant (CI) outcomes.

Methods: Ten prelingually deaf children, 4–6 years old, were recruited for the study. Twenty prelingually deaf subjects, 4–6 years old with CIs for 1 year, were also recruited; 10 with well-performing CIs, 10 with poorly performing CIs. Ten age and sex-matched normal-hearing children were recruited as controls. Visual ('sound' photo (photograph with imaginative sound) and 'non-sound' photo (photograph without imaginative sound)) evoked potentials were measured in all subjects. P1 at Oz and N1 at the bilateral temporal-frontal areas (FC3 and FC4) were compared.

Results: N1 amplitudes were strongest in the deaf children, followed by those with poorly performing CIs, controls and those with well-performing CIs. There was no significant difference between controls and those with well-performing CIs. 'Sound' photo stimuli evoked a stronger N1 than 'non-sound' photo stimuli. Further analysis showed that only at FC4 in deaf subjects and those with poorly performing CIs were the N1 responses to 'sound' photo stimuli stronger than those to 'non-sound' photo stimuli. No significant difference was found for the FC3 and FC4 areas. No significant difference was found in N1 latencies and P1 amplitudes or latencies.

Conclusions: The results indicate enhanced visual recruitment of the auditory cortices in prelingually deaf children. Additionally, the decrement in visual recruitment of auditory cortices was related to good CI outcomes.

【Keywords】prelingual deafness, cochlear implant, cross-modal plasticity

Introduction

It is generally accepted that one sense can benefit from the deprivation of another (1). This is observed in both blind and deaf individuals (2,3). In the prelingually deaf the auditory cortex can respond to visual stimuli, indicating cross-modal recruitment of auditory cortex by visual stimuli, known as cross-modal reorganization (4,5). Neuroimaging studies using functional Magnetic Resonance Imaging (fMRI) and magnetoencephalography (MEG) reveal that visual stimuli such as a moving dot pattern, can activate certain regions of the auditory cortex (Brodmann's areas 42 and 22) in prelingually deaf participants (4,6,7). In addition, some event-related potential (ERP) studies found larger ERP amplitudes and a greater anterior distribution of N1 components in deaf individuals when they processed the visual stimulus of an isoluminant color change (8).

The proposed mechanism behind this cross-modal reorganization is that long-term visual stimuli can lead to specialization of auditory cortex with engagement of specialized neural networks for hearing and language tasks. The evidence obtained from animal research and related literature review has also indicated the presence of visual cross-modal reorganization of auditory cortex in animal models (9-11). The presence of a visual-auditory modality in early life offers opportunities for change in individual behavior and audiological rehabilitation (12). A recent systematic review (12) of deaf induced cortical change showed that behavioral changes were accompanied by a reorganization of multisensory areas, ranging from higher order cortex to early cortical areas, highlighting cross-modal interactions as a fundamental feature of brain organization and cognitive processing. It was considered that the auditory cortex might reorganize to mediate other functions, for example vision, in areas of the superior temporal sulcus, just caudal to the primary auditory cortex with the result that deaf people show greater recruitment when processing visual, tactile or signed stimuli than normal hearing individuals (12).

Cochlear implants (CIs) have been widely used as an effective intervention tool for profound hearing impairment in children (13). Recent studies have indicated that CI effect on neuroplasticity of the central auditory system occurs only when adequate stimulation is delivered during a sensitive period in early childhood (14-17). Sharma and Dorman (2006) examined P1 latency in 245 congenitally deaf children fitted with CIs using evoked cortical potentials. They found that children had normal P1 latencies if they received their CIs before the age of 3.5 years, whereas after this time children showed abnormal or highly variable and delayed cortical response latencies (12,18). In Sharma et al. (19), significantly delayed cortical P1 responses generated from auditory thalamic and cortical areas were also found in children with CIs.

Cortical activity and visual cross-modal effects on the auditory cortex have been reported to play a role in CI outcomes. Lee et al. (2007) found hypometabolism in the temporal lobes of prelingually deaf children, speech scores post CI positively associated with enhanced metabolic activity in the prefontal cortex which contributes to auditory processing, and decreased metabolic activity in Heschle's gyrus which contributes to visual processing (20). Sandmann et al. (21) used parametrically modulated reversing checkerboard images to examine the initial stages of visual processing and confirmed visual take-over in the auditory cortex of CI users. In addition, the extent of visual processing in auditory cortices in postlingually deaf subjects was negatively related to CI outcomes (21).

Further evidence has suggested that many factors are associated with plasticity and CI outcomes in prelingually deaf individuals, such as the age at which the CI was received, cognitive abilities, family environment, etiology, and speech-language therapy. Of these factors, age at implantation contributes for most in terms of CI outcome in prelingually deaf children (16), i.e. younger age children with CI would achieve better speech outcomes. However, in Schramm et al. (22), although their results showed CI patients with prelinguistic deafness achieved significantly better speech understanding using phonetically balanced monosyllabic words, there was a wide range of performance across patients. They found that some older prelingually deaf children with CI also performed well in speech communication (22). They suggested this may be due to the various extent of visual cross-modal impact on the auditory cortex. Because of uncertainty in the status of auditory cortex plasticity without auditory stimuli before cochlear implantation, the effectiveness of CI outcomes is unlikely to be predicted for CI candidates, particularly for prelingually deaf children.

Recently, visual evoked potentials (VEPs) have been used to investigate visual-auditory cross-modality in patients with CIs. Visually evoked fronto-temporal N1 responses were reported to be related to visual processing in the auditory cortex (23-25). Kristi et al. (2011) reported that in postlingually deaf subjects, the higher N1 VEP responses in the right temporal lobe in children with a CI was related to poor speech perception (25). Moreover, different visual stimuli, ‘sound’ photo vs. ‘non-sound’ photo, have been reported to produce different N1 responses in the fronto-temporal area; i.e., ‘sound’ photo stimuli evoked stronger N1 responses than ‘non-sound’ photo stimuli in normal (26).

To our best knowledge, N1 VEP response to ‘sound’ or ‘non-sound’ photo stimuli in prelingually deaf children still remains unclear. Moreover, the relationship of visual processing recruitment of auditory cortices and auditory outcomes in prelingually deaf children with CIs is unknown. Therefore, in the present study, we examined the extent to which visual processing recruitment of auditory cortices occurred in prelingually deaf children with CIs. In addition, the relationship between the visual processing recruitment and auditory performance in these children was explored.

Materials and Methods

- **Participants**

Ten prelingually deaf children bilaterally profound hearing loss were recruited from special education schools for the deaf as the deaf group. There were five boys and five girls, aged between 4 and 6 years (mean age and SD: 4.4±0.7 years). Twenty prelingually deaf children fitted with a CI to the right side for at least one year were also recruited. The CIs fitted in this group of patients included: 10 MEDEL SONATAti100, 3 Cochlear Freedom (CI24RE), 7 Advanced Bionics (AB) HiRes 120. On the basis of their Category of Auditory Performance (CAP) score (22), they were divided into two groups. Ten subjects (4 boys and 6 girls, mean age 4.6±0.90 years old, range 3–6 years old) with CAP scores better than 5 were assigned to the CI good performer group, the remaining 10 (4 boys and 6 girls, mean age 4.4±1.0 years old, range 3–6 years old) with CAP scores less or equal to 5 were in the CI poor performer group (14). Ten age and sex matched normal-hearing children were recruited as the control group. **Table 1** provides detailed demographic information, together with communication mode (i.e., using sign language or oral communication) and socio-economic status.

Table 1 near here

Ethical approval was obtained from the Institutional Review Board at Sun Yat-sen Memorial Hospital at Sun Yat-sen University. Detailed information was provided to the parents and, written consent obtained before proceeding with the study.

- **Visual stimuli**

One ‘sound’ photo (i.e., a photograph with imaginative sound) and one ‘non-sound’ photo (i.e., a photograph without imaginative sound) were presented as visual stimuli in a similar way to the study of Proverbio (26). The photographs were chosen to ensure that most of the children were familiar with the images and understood their meaning. **Figure 1** shows the experimental block design, which consisted of an intermittent stimulus mode using ‘sound’ photo and ‘non-sound’ photo stimuli. For the ‘sound’ photo stimulus experiment, it consisted of 85 trials of ‘sound’ photo stimuli, and 15 trials of ‘non-sound’ photo stimuli as deviant stimuli. In contrast, for the ‘non-sound’ photo stimulus experiment, it consisted of 85 trials of ‘non-sound’ photo stimuli, and 15 trials of ‘sound’ photo stimuli as deviant stimuli. As shown in **Figure 1**, each stimulus was presented for 1 second, followed by one blank screen (1.7–1.9 seconds in duration) as the inter-stimulus. To make sure that the participants concentrated on the stimuli, one novel that consisted of 15 photographs was presented after 5–10 trials and the children were asked to press a button while the deviant photograph present.

Figure 1 near here

- **VEPs measurement**

ERPs were recorded from 128 scalp electrodes (Dense Array EEG System with HydroCel Geodesic Sensor Nets (EGI, OR, USA)). After installation of the 128-channel electrophysiological cap, the test took place in a soundproof and electrically shielded room. Each participant was asked to sit on a comfortable chair approximately

100 cm away from the 19-inch high-resolution VGA computer screen on which the visual stimuli were presented. The participants were instructed to watch the screen throughout the entire experiment, avoiding/minimizing body and eye movements. The impedance for each electrode was kept below 40 kΩ during the experiment (17).

The ERP responses were recorded continuously using Net Station 4.3 (EGI, USA) and analyzed off-line. The ERP signals were digitally filtered with a band-pass of 0.1–30 Hz and signals with a segment of 700 ms, including 100 ms of pre-stimulus baseline were collected. Any signal with an electro-oculography amplitude exceeding 75 µV was excluded as an artifact likely caused by eye movements or eye blinks. An amplitude exceeding 75 µV at any electrode site was defined as a poor channel. If there were six or more poor channels in a segment, then this segment was excluded as a bad segment. If fewer than six poor channels were present, the segment was considered valid and each poor channel was replaced with the average value obtained from its surrounding channels. The response waveforms evoked by the visual stimuli were obtained by averaging all valid segments. All responses at individual electrodes were referred to the average reference (27). The baseline was corrected according to the mean amplitude over the 100-ms pre-stimulus level.

All responses evoked by using either the 'sound' photo or 'non-sound' photo stimuli were recorded and averaged, respectively. **Figure 2** shows an example of ERP recordings obtained from an individual. The small-group average regions of interest were also analyzed (**Figure 3**). The N1 (the first negative response) at both FC3 (the left frontal-temporal area) and FC4 (the right frontal-temporal area) as well as the P1 (positive response occurring at approximately 170 ms) at Oz (the occipital area) were analyzed.

Figure 2 near here

Figure 3 near here

- **Statistical Analysis**

Multifactorial repeated-measures ANOVAs were performed for the ERP data analysis. The within factors were the stimulus categories (‘sound’ photo and ‘non-sound’ photo) and electrode sites (FC3 for the left side and FC4 for the right side), and the between factors were groups (deaf, poor CI performers, good CI performers, poor CI performers, and Controls). The alpha inflation caused by multiple comparisons was corrected using Greenhouse-Geisser corrections. The post-hoc Tukey’s test was also used for multiple comparisons.

Results

Clear N1 responses at both FC3 and FC4 were found in all groups. In addition, a P1 response was found at Oz. **Figure 3** shows an example of the N1 and P1 responses obtained from children in four groups when using ‘sound’ photo and ‘non-sound’ photo stimuli.

A 3-way RM-ANOVA was used with one between-subject factor (groups: Deaf, Poor CI performers, good CI performers, and Control) and two within-subject factors (stimuli: ‘sound’ and ‘non-sound’; electrode sites: FC3 and FC4) for N1 amplitudes and latencies. Additionally, a 2-way RM-ANOVA was used with one between-subject factor (group: Deaf, poor CI performers, Good CI performers, and control) and one within-subject factor (stimulus: ‘sound’ and ‘non-sound’) for P1 amplitudes and latencies.

Significant effects were obtained for group (F=44.747, p<0.001) and stimulus (‘sound’ photo > ‘non-sound’ photo, F=17.282, p<0.001) referring to N1 amplitudes (**Figure 4**). Group *stimulus* site interaction effects were also found to be significant

(F=5.483, *p*=0.003). No significant main effect was found for electrode sites of FC3 and FC4 (F=0.013, *p*=0.909).

A pairwise comparison found that N1 amplitudes in the deaf group were significantly larger than in the poor CI performers, good CI performers and control groups (P=0.008, *p* <0.001, and *p*<0.001, respectively). N1 amplitudes in the poor CI performers group were significantly larger than those in the good CI performers and normal groups (*p*<0.001 and *p*<0.001, respectively). No significant difference was found between the control and good CI performers groups (*p*=0.893).

Figure 4 near here

When comparing the effect of different stimuli, 'sound' photo evoked stronger responses than 'non-sound' photo at FC4 in the deaf and poor CI performers groups (F=8.82, *p*=0.005 and F=23.17, *p*<0.001, respectively) (**Figure 5**), but not in the good CI performers and control groups.

Figure 5 near here

With respect to N1 latencies, the main effects were obtained for electrode sites (FC4 149.3 vs. 142.8 FC3, F=7.538, *p*=0.009) and stimuli ('sound' photo 148.9 vs. 143.2 'non-sound photo, F=10.787, *p*=0.002). No significant main effect was found for the variable group (F=0.781, *p*=0.512). In addition, group*stimulus, group*site and stimulus*site interactions were not significant (F=2.409, *p*=0.083; F=0.879, *p*=0.461; and F=1.454, *p*=0.236, respectively).

With respect to P1 latencies and amplitudes, no significant main effect was found for the variable group (F=0.781, *p*=0.512 for latency; F=2.409, *p*=0.083 for amplitude). In addition, the group*stimulus interaction was not significant (F=2.409, *p*=0.083; F=0.879, *p*=0.461, and F=1.454, *p*=0.236, respectively).

Discussion

The present study examined visual processing recruitment of auditory cortex in prelingually deaf children with and without CIs in comparison to hearing controls. ‘Sound’ and ‘non-sound’ photos were used as the visual stimuli for VEP measurements. The advantage of using images associated with sounds is enhancement of visual activation of auditory cortex. Previous studies have shown a significantly larger P1 amplitude at the occipital midline in adults with mild-moderate hearing loss than controls when using a kind of visual stimulus called ‘high contrast sinusoidal concentric grating’ (28). Consequently, they suggested that visual enhancement in the occipital area is likely to be associated with better visual sensitivity in people with hearing impairment. Moreover, by using ‘sound’ photo and ‘non-sound’ photo stimuli, Proverbio et al. (26) found different ERP responses, i.e., strong N1 response in the frontal area and weak response in the occipital area, when compared with using visual motion stimuli, i.e., a strong N1 response in the occipital area and a weak response in the frontal area (2,25). Further comparison showed that the N1 response evoked by using the ‘sound’ photo was even greater than using ‘non-sound’ photo in the frontal area, which can be used as an indicator of auditory cortical recruitment by ‘sound’ photo visual stimuli.

In the present study, the prelingually deaf children without CIs had significantly greater N1 VEP amplitudes in response to the visual stimuli (both ‘sound’ and ‘non-sound’ photo stimuli) than the children with CIs and controls. Further analysis showed that N1 amplitudes were largest in the deaf children, followed by those with poorly performing CIs, controls and those with well-performing CIs, whilst there was no significant difference between controls and those with well-performing CIs. However, Buckley et al. (25), reported that only N1 VEP amplitudes from the right temporal lobe were negatively related to speech perception in prelingually deaf children with CIs when they used the stimuli of moving visual gradients located in a square pattern on a gray background with still pictures of cartoon characters. Differences in the stimulus category of the two studies may be responsible for the discrepancy between the two outcomes (25,26,29). Buckley et al. (25) used a vision motion stimulus in the peripheral visual field, while in the present study, we presented the stimuli centrally, which produced bilateral N1 response enhancement.

Furthermore, as shown in **Figure 4**, children who used a CI had lower N1 VEP amplitudes than deaf children, while those with well-performing CIs had lower N1 amplitudes than poor CI performers and similar N1 amplitudes as children with normal hearing. Although recruitment of auditory cortices evoked by the visual system to process the visual photos were found in deaf children with CI, the present result implies that there is a negative relationship between the process and CI outcomes. As indicated previously, visual cross-modal take-over has been demonstrated in postlingually deaf adults, which is related to the auditory performance of the patients after receiving a CI (30,31). The adaption process after a CI procedure may indicate a reversal of auditory functional take-over, while insufficient adaptation to the new input may be reflected by residual signs of visual take-over (31,32). In the present study, the positive relationship between the decrement of the N1 amplitudes and CI outcomes may demonstrate the reversal of auditory functional take-over. Further studies are needed to determine the relationship between decrement of N1 amplitude and the auditory performances in deaf children.

The other interesting finding obtained from the present study is that ‘sound’ photo evoked greater N1 amplitude compared to ‘non-sound’ photo, which is consistent with the findings of Proverbio et al. (26). However responses evoked by using ‘sound’ photo were greater than using ‘non-sound’ photo only at FC4 in the deaf and poor CI performers, but not in the good CI performers and controls. Buckley et al. (25) found that the amplitudes of N1 VEP responses in the right temporal area were negatively related to the speech performances of the CI patients. It is considered that the left and right temporal lobes play different roles in processing auditory information. The right lobe mainly participates in speech perception tasks in subjects with normal hearing and varies according to the degree of residual hearing. Right temporal lobe structures can be recruited for speech perception processing if the speech signal is degraded (33) and seems to be important for underlying meaning in message extraction (34). However, the left temporal lobe mainly processes fine structures of speech signals (35). In addition, several studies with deaf individuals and CI users have shown that the effect of deprivation-induced cross-modal plasticity has primarily been localized to the right hemisphere (4,31,35-37), either because the right hemisphere is more susceptible to reorganizational changes compared with the left hemisphere (37) or because the right hemisphere is more involved in the processing of sounds with low complexity (38).

It is noteworthy that the present results were only obtained from the participants with a CI on the right side. Although bilateral CIs are generally recommended for children with bilateral sever to profound hearing impairment, due to their affordability, a majority of the suitable candidates were only fitted with a CI unilaterally. It is interesting to investigate the similarity or significant difference in terms of the effects on visual processing recruits the auditory cortices in comparison of children with a unilateral CI (on either right ear or left ear) and those with bilateral CIs in the future study.

Conclusions

The influence of visual processing recruitment of the auditory cortices is evident as there were stronger N1 VEP responses in prelingually deaf children and there were decrements in this recruitment in children with a CI. The recruitment decrement was related to good CI outcomes. Consideration of the bilateral N1 response to the visual stimuli, and also the difference in the frontal response to the ‘sound’ photo and ‘non-sound’ photo in prelingually deaf children without and with CI, the ’sound and non-sound’ indicates that photos are feasible for the studying of visual recruitment of auditory cortex. Further exploration and follow-up studies to determine visual impacts on auditory cortices and their influence on auditory outcomes with a CI are needed.

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