Event Related Potential Evidence of Enhanced Visual Processing in Auditory Associated Cortex in Adults with Hearing Loss

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Short title: Visual Processing in Hearing Loss

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Abstract:

Objective: The present study investigated the characteristics of visual processing in auditory associated cortex in adults with hearing loss using event-related potentials (ERP).

Methods: Ten subjects with bilateral postlingual hearing loss were recruited. Ten age- and sex-matched normal hearing subjects were included as controls. Visual ('sound' and 'non-sound' photos) evoked potentials were performed. The P170 response in the occipital area, as well as N1 and N2 responses in FC3 and FC4 were analyzed.

Results: Adults with hearing loss had higher P170 amplitudes, significantly higher N2 amplitudes and shorter N2 latency in response to 'sound' and 'non-sound' photo stimuli at both FC3 and FC4, with the exception of the N2 amplitude which responded to 'sound' photo stimuli at FC3. Further topographic mapping analysis revealed that patients had a large difference in response to 'sound' and 'non-sound' photos in the right frontotemporal area, starting from approximately 200 ms to 400 ms. Localization of source showed the difference to be located in the middle frontal gyrus region (BA10) at around 266 ms.

Conclusions: The significantly stronger responses to visual stimuli indicate enhanced visual processing in auditory associated cortex in adults with hearing loss, which may be attributed to cortical visual re-organization involving the right frontotemporal cortex.

Introduction

Hearing loss is one of most common sensory problems in adults. It is reported that up to 33% of the over 65's have a disabling hearing loss (WHO, 2014). The type of hearing loss can be categorised as pre-lingual or post-lingual. Pre-lingual hearing loss is usually associated with hereditary factors, whilst post-lingual loss is typically associated with aging, exposure to noise and infections (Manchaiah et al., 2017). Adults with hearing loss may have communication difficulties in social contexts and at work, particularly where the loss is severe or profound, leading in the long term to loneliness, central deprivation and changes in cortex plasticity (Manchaiah et al., 2017; Campbell et al., 2014).

The primary auditory cortex is located bilaterally in superior areas of the temporal lobe approximating to Brodmann Areas (BAs) 41, 42, and partially BA22 (Fine et al., 2005). Auditory stimuli mainly activate the auditory cortex; however, neuroimaging data suggests a multisensory integration of inputs from audio and visual modalities (Hocking and Price, 2008). Finney et al. (2001; 2003) found that visual stimuli could activate regions of the auditory cortex (BA42 and BA22) in deaf subjects, supporting the concept of audio/visual interaction. The loss of one sensory modality, as in deafness, may induce an increment in performance of other modalities, e.g., visual ability. This might be accounted for by compensatory mechanisms and re-organization. Enhanced visual performance might also be reflected in the enhanced "reactivity" of the auditory cortex to visual events (Pavani and Bottari, 2012).

Behavioral studies show that people with hearing loss have better visual ability in certain areas than those with normal hearing, such as in the processing of the visual periphery or motion under conditions of attention (Fine et al., 2005; Bavelier et al., 2006; Hocking and Price, 2008). Such enhancement in behavioral domains might be due to visual re-organization, i.e., cross-modal re-organization between the visual and auditory cortex, with visual processing in the auditory cortex (Bavelier et al., 2006;

Hocking and Price, 2008). Evidence from cortical function change also supports the visual re-organization seen in hearing impaired subjects post cochlear implant (CI). For example, Lee et al. (2007) found that temporal lobe activity decreased in congenitally deaf patients and there was a negative correlation between speech recognition rate and activity recorded from the Heschl's gyrus region in hearing impaired subjects after CI. This suggests that excessive activity of visual central function is inhibited by the development of hearing sensitivity after CI. In addition, Sandmann et al. (2012) showed increased activity in visual stimulus-related auditory areas in adults with post-linguistic deafness using visual evoked event-related potentials (ERP). The decline of visual activation in the auditory cortex after CI was positively correlated with speech recognition ability.

Most studies have however been conducted on deaf individuals with profound hearing loss, whereas post-lingually deaf adults usually show a gradual decline in hearing, typically progressing through mild, moderate, severe, and profound stages (Pavani and Bottari, 2012; Campbell and Sharma, 2014). In the early stages, i.e., mild or moderate hearing loss, their speech discrimination ability declines (Campbell and Sharma, 2014). To better communicate with others, they typically use sign language or lip-reading. This might enhance visual ability and cross-modal re-organization affecting auditory rehabilitation. Recently, Campbell and Sharma (2014) found that adults with early hearing loss had significantly larger P1, N1, and P2 amplitudes, decreased N1 latency and activation of auditory-associated cortex in response to visual stimuli. They concluded that visual cross-modal re-organization started in the early stages of hearing impairment. However, they focused on the mild to moderate stage where subjects can communicate well, potentially even unaware of a hearing loss. It is generally assumed that subjects with a hearing loss worse than moderate typically have to use visual information to assist communication. Therefore, cross-modal re-

organization might be more significant, leading to poor audiological rehabilitation outcomes (Pavani and Bottari, 2012).

Various studies have shown that different types of stimuli are used to investigate the cross-modal re-organization mechanism, such as parametrically modulated reversing chequerboard images (Sandmann et al., 2012) or circle-star patterns (Campbell and Sharma, 2014). However, most studies used visual stimuli without any relation to auditory communication. In 2011, Proverbio et al. (2011) reported using photos with or without imaginative sound as the visual stimulus, i.e., 'sound' photo vs. 'non-sound' photo. They found that 'sound' photos (photos with imaginative sound) evoked larger N1 and N2 responses in the frontotemporal cortical area than 'non-sound' photos (photos without imaginative sound), implying that the auditory cortex plays a role in the processing of visual information. Therefore, as a result of poor auditory ability, subjects with hearing loss might have more auditory processing of visual information because they intend to rely on visual compensation.

In our previous studies, we used 'sound / 'non-sound' photo stimuli to investigate the evoked potentials of prelingually deaf children. The results suggested intra- or cross-modal reorganization and higher primary visual cortex activation and reflect a stronger potential for cortical plasticity. Furthermore, prelingually deaf children were more sensitive to 'sound' photos than 'non-sound' photos (Liang et al., 2014, 2017). In addition, a recent study by Anderson (2017) used lip-reading related photo stimuli in CI adults and found increased activation of the superior temporal gyrus (auditory related area) of adults before CI related to the better auditory speech level 6 months after CI.

However, visual processing in the auditory cortex was not well presented. Adults with gradual onset moderate to severe hearing loss may provide an ideal model for the study of visual processing in the auditory cortex. To our best knowledge, few studies have focused on this subject group.

In line with the traditional view that deaf subjects are more prone to visual communication and the available literature, we hypothesized that they would provide a more sensitive group for the detection of cross-modal activation of auditory regions by 'sound' stimuli. In this study, we examined visual-evoked potentials (VEP) using high-density electroencephalography in subjects with adult-onset moderate or worse hearing loss. We aimed to elucidate the characteristics of visual stimulus processing, especially regarding the difference between responses to photos that suggest and do not suggest sound, and to confirm the role of the auditory cortex in processing visual information and estimate cortical visual reorganization and its mechanism.

Materials and Methods

Participants

A total of 10 participants with bilateral moderate to severe hearing loss (four women and six men aged from 26 to 52 years old) were recruited to the present study. Hearing thresholds are shown in Figure 1. The history of hearing loss ranged from 2 to 8 years. None of the participants reported having a history of neural disorders. All participants had normal or corrected-to-normal vision.
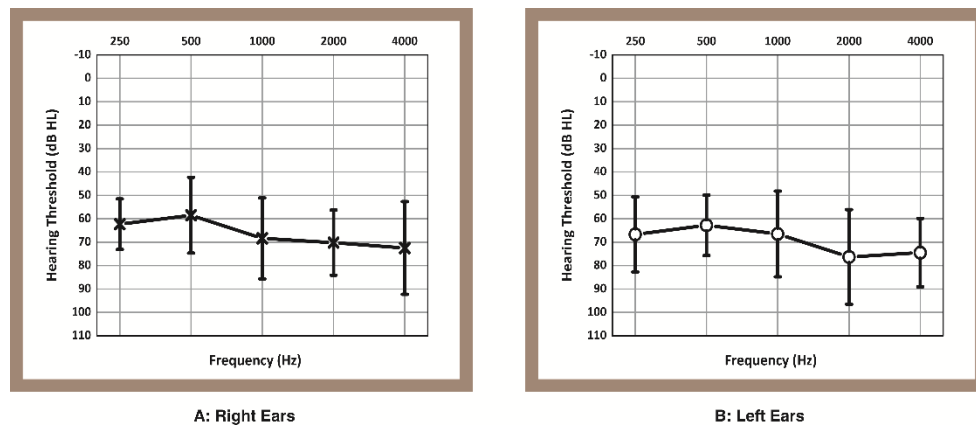
Figure 1. Audiometric threshold characteristics of subjects with hearing loss.
Hearing thresholds, ±2 standard deviations, for frequencies from 250 Hz to 4000 Hz

Ten age- and sex-matched volunteers with normal hearing were recruited as controls. Participants took part on a completely voluntary basis. All participants were informed regarding the nature of this study and their involvement.

*ERP measurement: experiment design and analysis*

ERP responses were measured using a 128-Channel Dense Array EEG System with HydroCel Geodesic Sensor Nets (EGI, USA). The test was performed in a soundproofed and electrically shielded room. Each participant was requested to sit on a comfortable chair, approximately 100 cm away from a high-resolution VGA computer screen, which was used to show photos as visual stimuli. Participants were instructed to observe the screen during the entire experiment, avoiding/minimizing body and eye movement. All electrode impedances were maintained at less than 40 kΩ during the experiment (Liang et al., 2014).

Visual stimulus selection

The 'sound' photo or 'non-sound' photo procedure was adopted from the study by Proverbio et al. (2011), i.e., a pilot study was conducted with 30 normal hearing volunteers in order to choose the most appropriate 'sound photo' or 'non-sound photos' for the ERP measurement. 30 photos that evoked a strong auditory feeling ('sound' photo) and 30 photos that did not ('non-sound' photo) were selected. They were matched in size (350*350 pixels) and luminance (43.92 cd.cm^{-2}). Photos were presented randomly to the volunteers via Eprime 2.0$^{®}$ (Sharpsburg, PA, USA). They were then requested to respond to the photo by pressing the button '1' for 'sound' photo, and '0' for 'non-sound' photo. A 'sound' photo and a 'non-sound' photo with 100% correct rate and the shortest average response time were chosen for the ERP measurement. Moreover, before the ERP measurement, all participants were asked to confirm recognition of the chosen 'sound' photo and 'non-sound' photo.

The visual stimuli trials were similar to those used in our previous study in prelingually deaf children (Liang et al., 2014, 2017). Figure 2 shows the experimental

block design, which consisted of an intermittent stimulus mode using 'sound' and 'non-sound' photo stimuli. The 'sound' photo stimulus experiment consisted of 85 trials with 'sound' photo stimuli and 15 trials with 'non-sound' photo stimuli as deviant stimuli. In contrast, the 'non-sound' photo stimulus experiment consisted of 85 trials with 'non-sound' photo stimuli and 15 trials with 'sound' photo stimuli as deviant stimuli. Each stimulus was presented for 1 sec, followed by a blank screen for 1.2–1.7 sec as the inter-stimulus interval. The participants did not need to give any response to the standard or deviant stimuli. To make sure that participants concentrated on the stimuli, one novel stimulus that consisted of one out of 15 photographs was presented after 5–10 trials, and the participants were asked to press a button while the novel photograph. To overcome any initial unfamiliarity with the setting and improve the accuracy rate of the responses, a clear instruction for the test procedure together with a practical session was provided. This is important to improve the reliability and accuracy of the experiment. As a result, in the present study, the accurate response rate found in the participants was greater than 90% (i.e., there were less than three missing or wrong responses).
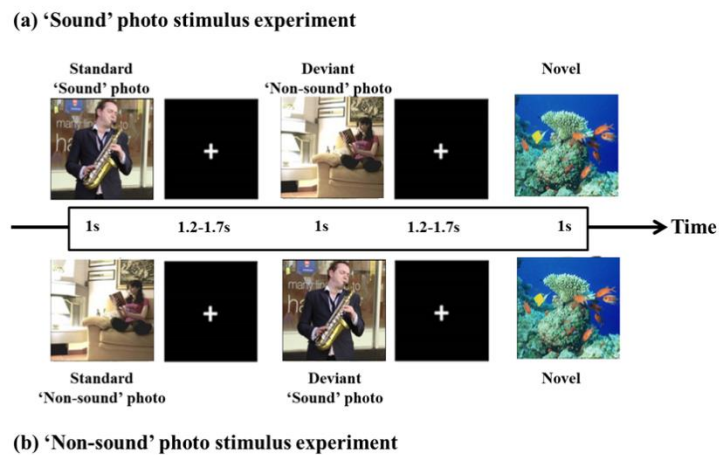
Figure 2. Diagram of the sequence of visual stimuli   A total of 100 stimuli, 85% for standard and 15% for deviant. At least one standard stimulus was presented before each deviant stimulus was given. (a) 'sound' photo stimulus experiment; (b) 'non-sound' photo stimulus experiment.

ERP data analysis

ERP responses were recorded continuously using Net Station 4.3 (Electrical Geodesics, Inc., Eugene, OR, USA) and then analyzed off-line.   ERP signals were digitally filtered with a band-pass of 0.1–30 Hz. 700ms signal segments, including 100ms as a pre-stimulus baseline, were collected.   Artifact detection was set to the default artifact rejection algorithm setting of the Net station 4.3 (Luu et al., 2011, 2016). Any signals with amplitudes on electro-oculography (EOG) exceeding 75 µV were excluded as artifacts likely to be caused by eye movement or blinking. Any electrode site with significant artifacts 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 waveforms evoked by standard and deviant stimuli were analyzed by averaging all valid segments. All responses at individual electrodes were referred to the average reference (Jung et al., 2006; Liang et al., 2017). The baseline was corrected according to the mean amplitude over the 100ms pre-stimulus period. According to the study design shown in Figure 2, the analysis of the response to 'sound' photo was calculated all responses obtained from the 'sound' photo stimuli in both 'sound' photo stimulus experiment (a) and the 'non-sound' photo stimulus experiment (b). Similarly, the analysis of the response to 'non-sound' photo was calculated all responses obtained from the 'non-sound' photo stimuli in both experiments. As a result, the difference between the response to 'sound' photo and the response to 'non-sound' photo was calculated.

As published previously, regions related to the auditory associated cortex around FC3 (left frontal-temporal area) FC4 (right frontal-temporal area) and Pz (occipital area related to the visual cortex) were chosen for recording (Figure 3) (Liang et al., 2017). Considering the possible bias from using results from a single electrode, as shown in

Figure 3, averaged data were obtained from several electrodes in a small region near FC3, FC4 and Pz. In addition, N1 (the first negative response), N2 (the second negative response), configuration, peak latency, and amplitude were recorded and analyzed.
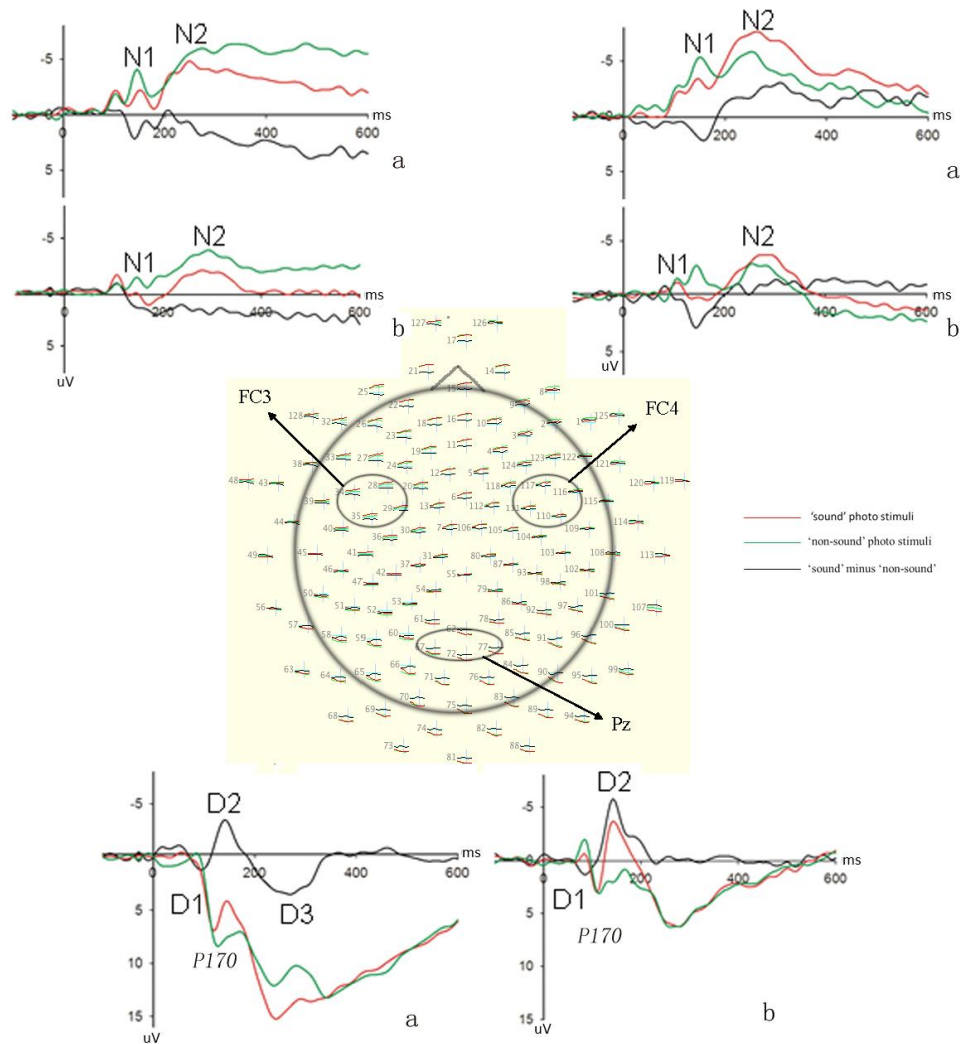
Figure 3. Regions of interest (ROIs) for visual and auditory area Sensor layout for the 128-channel Hydrocel Geodesic Sensor Net. The occipital area, Pz, and frontotemporal areas, FC3 and FC4, were analyzed.

Topographic mapping (Matlab, MathWorks, USA) was performed to investigate the spatial and temporal disparities between hearing impaired participants and normal hearing controls. Source estimates were performed using a minimum norm solution with LAURA (Local Auto Regressive Average) in GeoSource electrical source imaging

software (Version 1.0, EGI, USA) (Luu et al., 2011), which describes the neural sources of the target scalp potentials. All source estimates were performed using grand-averaged scalp data.

Statistical Analysis

Multifactorial repeated measures were applied to the ERP data using the within-subject factors of stimulus category ('sound', 'non-sound'), and electrode site (according to the ERP components of interest) and the between-subjects factor of hearing level group (patients and controls). The alpha inflation due to multiple comparisons was corrected by means of the Greenhouse-Geisser correction. The accordingly modified degrees of freedom are reported, together with ε and corrected probability level. The least significant difference (LSD) was calculated between groups when ANOVA results were significant.

Results

Waveforms of interest across the whole head (128 channels) are shown in Figure 3. Three obligatory cortical VEP components elicited in response to the visual stimuli were analyzed, i.e., P170 (occurring at approximately 170 ms) at Pz; N1 (occurring at approximately 100 ms) and N2 (occurring at approximately 250-300 ms) at FC3 and FC4 (Table 1). Table 1 summarizes the averaged latencies and amplitudes in response to 'sound' and 'non-sound' photo stimuli in both hearing impaired participants and controls at Pz, FC3 andFC4.

To investigate the N1 and N2 latencies and amplitudes, a three-way RM-ANOVA was conducted with, one between-subject factor (patient and control) and two within-subject factors (stimulus factor: 'sound' photo and 'non-sound' photo; electrode site factors: FC3 and FC4). For P170 latencies and amplitudes, a two-way RM-ANOVA was used with one between-subject factor (patients and controls) and one within-subject factor (stimulus factor: 'sound' photo and 'non-sound' photo).

Table 1. The latencies and amplitudes in response to 'Sound' and 'Non-sound' stim

	Control Group (n=10)		Patient Group (n=10)		Main effects and interactions	*F* value	*P* value
	'Sound'	'Non-sound'	'Sound'	'Non-sound'			
N1: Mean (SD)							
Latency (FC3, ms)	112.1(2.2)	111.6 (2.5)	106.4(2.4)	113.4(2.7)	Groups	0.083	0.777
Latency (FC4, ms)	108.4(3.5)	112(2.4)	110.5(2.6)	110.8(2.6)	**Stimuli[#]**	**5.784**	**0.030**
					Electrode sites	0.292	0.343
Amplitude (FC3, uV)	-1.5(0.8)	-1.1(0.5)	-1.3(0.8)	-1.4(0.5)	Groups	0.499	0.492
Amplitude (FC4, uV)	-1.1(0.8)	-1.0(0.9)	-2.2(0.8)	-2.8(0.9)	Stimuli	0.012	0.913
					Electrode sites	0.838	0.236
N2: Mean (SD)							
Latency (FC3, ms)	287.4(2.0)	283.6(2.4)	248.3(16.4)	250.5(2.5)	**Groups[#]**	**10.252**	**0.008**
Latency (FC4, ms)	287.3(2.5)	287.4(2.4)	249.5(2.6)	248.9(2.6)	Stimuli	0.343	0.524
					Electrode sites[#]	**5.942**	**0.032**
					Group* stimuli*sites[#]	**4.421**	**0.032**
Amplitude (FC3, uV)	-2.5(1.0)	-3.4(0.8)	-8.3(1.1)	-5.9(0.8)	**Groups[#]**	**8.831**	**0.006**
Amplitude (FC4, uV)	-4.0(1.5)	-2.9(1.4)	-8.5(1.6)	-7.6(1.5)	**Stimuli[#]**	**18.423**	**0.0001**
					Electrode sites[#]	**9.265**	**0.005**
					Group*stimuli*sites[#]	**5.592**	**0.004**
P170							
Latency (Pz, ms)	148(12.3)	150(10.8)	160(14.6)	164(20.8)	Groups	0.984	0.831
					Stumili	1.783	0.434
Amplitude (Pz, uV)	2.6(0.8)	2.7(0.7)	7.5(1.1)	8.4(1.0)	**Groups[#]**	**6.819**	**0.021**
					Stumili	1.329	0.116
					Group*stimuli	1.248	0.185

[#]: Statistical significance found in main effects or interactions.

Looking at the N1 component significant effects were seen only within the stimuli ($F_{1,15}=5.784$, $p=0.03$) for the latencies, and the faster N1 response time for 'sound' photo (109.4±7.1ms) over "non-sound" 112.4±7.4 ms). There was no interaction effect cross group ($F_{1,15}=0.083$, $p=0.777$) or electrode sites ($F_{1,15}=0.292$, $p=0.343$). For N1 amplitude, there were no significant effects for groups ($F_{1,15}=0.499$, $p=0.492$), stimuli ($F_{1,15}=0.012$, $p=0.913$) or electrode sites ($F_{1,15}=0.838$, $p=0.236$).

In respect of the N2 component when comparing N2 amplitudes, significant effects were found for groups ($F_{1,15}=8.831$, $p=0.006$), stimuli ($F_{1,15}=18.423$, $p=0.0001$) and electrode sites ($F_{1,15}=9.265$, $p=0.005$). Group* stimuli*sites interaction effect was also significant ($F_{1,15}=5.592$, $p=0.004$).

The simple effect test showed that adults with hearing loss had a significantly higher N2 amplitude in response to 'sound' photos at both FC3 ($F_{1,15}=4.612$, $p=0.049$) and FC4 ($F_{1,15}=6.883$, $p=0.019$), and also to 'non-sound' photos at FC4 ($F_{1,15}=9.054$, $p=0.009$). For the patient group, a pairwise comparison showed that N2 amplitudes to be higher in response to 'sound' photos than 'non-sound' photos at the FC4 electrode sites (LSD, $p=0.002$). However, at FC3, the 'non-sound' photos evoked higher N2 amplitudes (LSD, $p=0.012$). In controls, within-subject factors analysis showed that only at FC4, was the N2 amplitude in response to 'sound' photos higher than that to 'non-sound' photos (LSD, $p=0.02$).

With respect to N2 latency, the main effects were obtained for groups and sites ($F_{1,15}=10.252$, $p=0.008$, and $F_{1,15}=5.942$, $p=0.032$), but not for the stimuli ($F_{1,15}=0.343$, $p=0.524$). In addition, group*site*stimuli interaction was significant ($F_{1,15}=4.421$, $p=0.032$). The simple effect test found shorter N2 latencies in response to 'non-sound' photos in patients with hearing loss than in controls ($F_{1,15}=9.773$, $p=0.007$), and pairwise comparison showed that the difference only exists at FC4 (LSD, $p=0.04$).

In respect of the P170 amplitude a significant effect was found for the groups (patients vs. controls, $F_{1,15}=6.819$, $p=0.021$), but not the stimuli ('sound' photo vs. 'non-

sound' photo, $F_{1,15}=1.329$, $p=0.116$). The group*stimuli interaction was found to be significant (F=1.248, $p=0.185$). Further analysis showed higher P170 amplitudes in patients than controls in response to 'sound' photo (LSD, $p= 0.023$) and 'non-sound' photo (LSD, $p=0.036$). For P1 latency, no significant main effect was found for groups ($F_{1,15}=0.984$, $p=0.831$), nor for the stimuli ($F_{1,15}=1.783$, $p=0.434$).
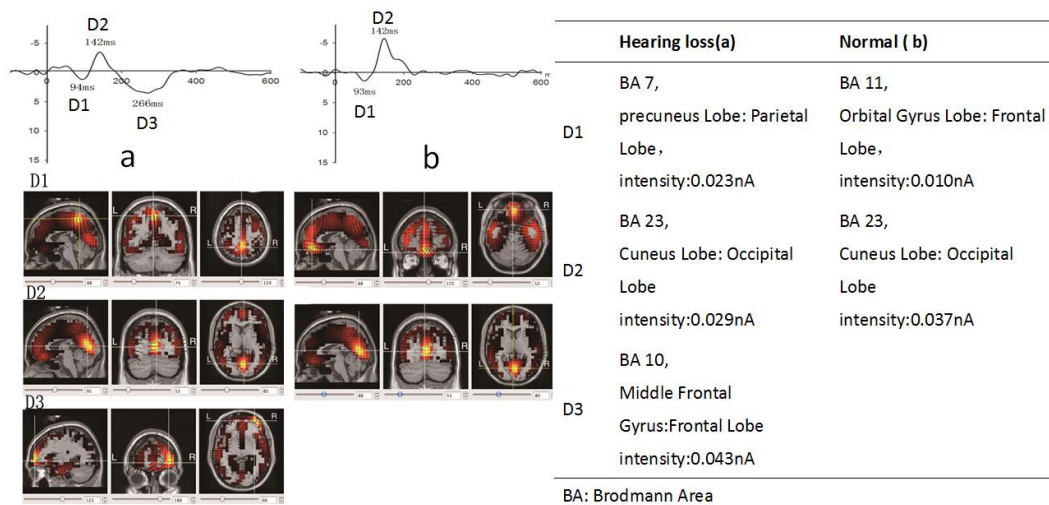
Figure 4 demonstrates the scalp topographies and a schematic description of the difference between processing 'sound' and 'non-sound' photos. The difference started 160 ms after stimulus presentation in the occipital area in both hearing impaired patients and normal hearing controls, lasting for about 20 to 40 ms. There was then a difference in the right frontotemporal area, starting from about 200 ms to 400 ms, reaching its peak at approximately 300 ms in hearing impaired patients. However, little difference was found in the normal hearing controls.
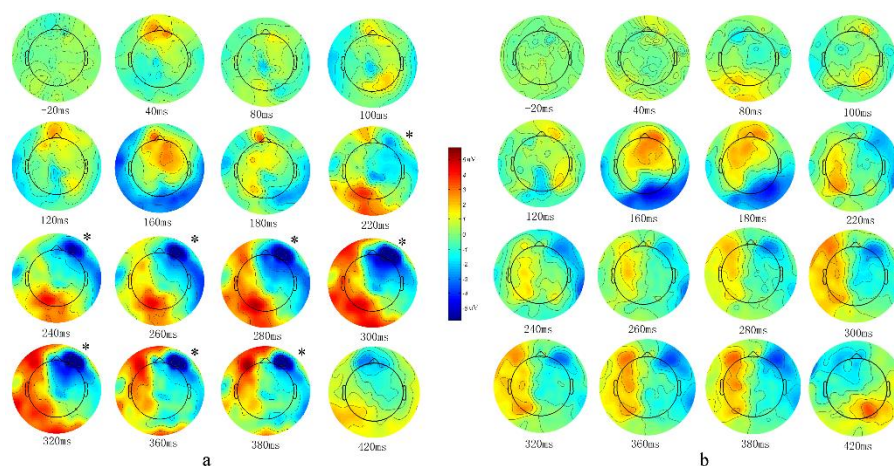
Figure 4. Spatiotemporal grand-mean difference between 'sound' and 'non-sound' photos a: Hearing loss subjects: the difference started from around 220 ms to 380 ms, in the right frontotemporal area. In the occipital area there was a very small difference at approximately 160 ms. **b**: Normal hearing controls: the difference was mainly in the occipital area at approximately 160 ms.

Source estimation of the difference between the response to 'sound' and 'non-sound' photos at Pz is shown in Figure 5. The source estimation was obtained using the peaks of the difference (94 ms, 142 ms, and 266 ms in adults with hearing loss, and 94 ms and 142 ms in normal hearing controls). The difference between 'sound' and 'non-

sound' photos activated the orbital gyrus and then the cuneus lobe in the normal hearing control group.

	Hearing loss(a)	Normal (b)
D1	BA 7, precuneus Lobe: Parietal Lobe，intensity:0.023nA	BA 11, Orbital Gyrus Lobe: Frontal Lobe，intensity:0.010nA
D2	BA 23, Cuneus Lobe: Occipital Lobe intensity:0.029nA	BA 23, Cuneus Lobe: Occipital Lobe intensity:0.037nA
D3	BA 10, Middle Frontal Gyrus:Frontal Lobe intensity:0.043nA	

BA: Brodmann Area

Figure 5. Source estimation for the response difference between "sound" and "non-sound" photos The cortical activation is shown from red to yellow (yellow reflects a stronger response) in sagittal, coronal, and horizontal views. (a) There were three clear peaks, D1, D2, and D3, in adults with hearing loss (b) There were two peaks in normal hearing controls

Discussions

In this study, we found subjects with hearing loss to have visual enhancement in the occipital area and larger N2 responses in the right frontotemporal area, especially to 'sound' photos. The difference in response to "sound" and "non-sound" photos was most clear at 200 ms to 400 ms (N2), which is a second processing stage (Kouider et al., 2013). However, there was no obvious difference in the early processing stage, i.e., 100–150 ms, N1. It has been shown previously that early processing is linearly related to the stimulus (energy or duration), whilst secondary processing is characterized by nonlinear brain activity relating to the meaningfulness of the stimulus (Del Cul et al., 2007). Thus, we ascertained that the advantage to subjects with hearing loss in dealing with sound information in photos was mainly in the nonlinear late stage of brain processing in the frontotemporal region and may be due to cortical visual reorganization.

Many studies have shown that deaf subjects have more sensitive visual abilities. Two neural mechanisms have been posited to account for the effect of deafness on vision (Lee et al., 2007; Pavani and Bottari, 2012). The loss of auditory inputs from the direct projections from auditory to visual areas might enhance the susceptibility of visual areas to visual inputs and visual top–down control (Bavelier et al., 2006). Another mechanism may be cross-modal reorganization of the temporal cortex such that visual stimuli activate the regions that normally respond predominantly to sounds (Calvert et al., 1997; Petitto et al., 2000; Ruytjens et al., 2007). Neville and Lawson (1987) showed that deaf individuals performed faster and better than normal hearing controls when attending to a visual location. Furthermore, using functional magnetic resonance imaging, some studies have demonstrated enhanced occipital responses to visual stimuli in deaf subjects (Anderer et al., 2004; Mitchell and Maslin, 2007), and suggested that visual enhancement in occipital areas might account for the more sensitive visual abilities. Consistent with previous studies, our present study has found occipital enhancement in hearing loss subjects, regardless of whether presented with a "sound" or "non-sound" photo, demonstrating visual compensation in hearing loss subjects (Bavelier et al., 2006; Pavani and Bottari, 2012). However, although we used visual stimuli with different sound information in the present study, there was no obvious difference in the occipital cortex response. Therefore, a visual compensation advantage alone cannot explain the more sensitive discrimination ability of deaf subjects.

Proverbio et al. (2011) used high-density ERPs in normal hearing participants and found that 'sound' images can activate the primary auditory cortex after 200 ms (N2), confirming that even in normal hearing subjects, visual stimuli can evoke the auditory sense. We also found that normal hearing subjects had stronger N2 responses to 'sound' photos than to 'non-sound' photos. Compared to normal hearing subjects, subjects with postlingual hearing loss had a stronger N2 response at FC3 and FC4, which is related

to the auditory associated cortex (Fuster, 2002; Hwang et al., 2005) and late stage processing (Kouider et al., 2013). Further, the cortical response to "sound" photos showed a frontotemporal enhancement in deaf subjects relative to 'non-sound' photos. As previously reported by Wu et al. (2011), the increase in anterior N2 amplitude while imagining an auditory stimulus suggests activation of an auditory mental representation. Therefore, the involvement and enhancement of right frontotemporal processing might account for the visual processing characteristics of deaf subjects, which supports a mechanism of cross-modal reorganization of the temporal cortex. Consequently, this might be the reason for the enhancement of lipreading.

Lee et al. (2007) found that deaf patients and control subjects performed equally well in a visual lipreading task, but deaf patients activated the left posterior superior temporal cortex more than controls. Finney et al. (2001; 2003) found that deaf subjects exhibited activation in BA42 and BA22 with visual stimulation, demonstrating that deafness results in enhanced processing of visual stimuli in the auditory cortex. Strelnikov et al. (2013) reported findings in postlingual deaf adults by analyzing brain activity and its change 6 months post-cochlear implantation when presenting visual stimuli. They found strong positive correlations in areas outside the auditory cortex and the highest positive correlations was found between a visual processing region and the posterior temporal cortex known to be related to audiovisual integration. Furthermore, Lee et al. (2001) found cross-modal plasticity in prelingual deaf subjects, suggesting that enhanced visual ability was related to cross-modal plasticity. In accordance with these findings this study showed enhancement of the N2 response in deaf subjects, suggesting cross-modal plasticity after hearing loss in adults. Moreover, our time-locked brain topographic mapping shows that the processing of "sound" and "non-sound" photos was different, especially in deaf subjects during late stage processing from about 200 ms to 400 ms in the frontal area.

Source localization measurement showed that 'sound' and 'non-sound' photos activated different visual processing regions, the orbital gyrus and the cuneus lobe, respectively in the normal hearing control group, which is in accordance with previous findings (Kellermann et al., 2012; Campbell and Sharma, 2014). However, for the adults with hearing loss, early activation was found in BA7, the precuneus lobe, which is related to working memory and visuospatial imagery, though activation of the cuneus lobe was weaker than in the normal hearing controls. Furthermore, there was a clear response at approximately 266 ms in the middle frontal gyrus (BA10), this only occurred in association with a strong N2 response in subjects with hearing loss. This is likely related to the complex integration of brain information (Proverbio et al. 2011). This is similar to the perceptual-cognitive machinery processing auditory speech (Auer, 2010). It has been suggested that the frontocentral N2 response indexes the stage of multisensory integration, with visual inputs coming from the ventral stream (Proverbio et al., 2011). Additionally, the frontal lobe was judging the information (Fuster, 2002). Therefore, our result further confirms the advantage of deaf subjects in discriminating auditory information using their visual ability through enhancement of processing in the auditory associated cortex, primarily in the late stage.

There are however other studies demonstrating that deafness does not take advantage from visual ability (Brozinsky and Bavelier, 2004; Bavelier et al., 2006). This might be due to methodological differences as the investigators selected different conditions, e.g., attentive/nonattentive and various groups of deaf subjects, e.g., different age, language, and etiology (Rettenbach et al., 1999; Bavelier et al., 2006). Furthermore, Rettenbach and colleagues showed that visual compensation for deafness is limited to attention-dependent tasks and does not develop until adulthood (Rettenbach et al., 1999). It is believed that deaf people do not have super-sensitive visual ability but that since they rely on their sense of vision more than normal hearing people they become more "aware." It was also suggested that people with normal

hearing could achieve such greater awareness too, if they just practiced the use of those senses. Not all blind individuals have more sensitive auditory ability, but since they use the sense of hearing more than sighted people, they become more "aware" of it (Lessard et al., 1998). For example, blind subjects were better at locating the source of sounds (Lessard et al., 1998). Therefore, feedback is necessary for the full development of the ability to localize sounds and is not consistent with the position that compensatory mechanisms involving other senses can replace the role of visual feedback. A similar phenomenon may also be present in deaf subjects. In our present study, the subjects were asked to concentrate on visual stimuli and respond to the displayed photo, which can guarantee their attention. Furthermore, all subjects were postlingually deaf. Although they did not receive any specific training of their visual ability, to be able to communicate efficiently, deaf patients usually attend to their visual ability and practice their use of vision. In real life it is unsurprising that deaf subjects would concentrate on communication and any auditory information content in a visual message.

Although a previous study had shown enhanced activation in response to visual stimuli in deaf subjects, the neuroimaging had a low temporal resolution (Menon and Kim, 1999), which limited the detection of visual processing. ERP-based methods have accurate temporal resolution, which is advantageous in studying neural processing. Moreover, using ERPs, brain activity can be elucidated using methods such as low-resolution brain electromagnetic tomography applied to ERPs (LORETA) (Anderer et al., 2004; Sandmann et al., 2012). Sandmann et al. (2012) found that in deaf adults with cochlear implants, visual stimuli evoked smaller P100 amplitudes and reduced visual cortex activation, confirming a visual take-over of the auditory cortex. Bottari et al. (2011) found that P1 peak amplitudes predicted response times in deaf subjects, whereas in hearing individuals' visual reactivity and ERP amplitudes correlated only at a later stage of processing, showing that long-term auditory deprivation can profoundly alter visual processing from the earliest cortical stages.

However, this study needs to be considered in light of several limitations. Firstly, there was not an exact behavior evaluation of subjects' visual compensation, so the relationship between visual behavior and cortical processing is still not clear. Secondly, we used the default setting of the Netstation (EGI, USA) to analyze the EEG data because it is approved as a reliable method for the artifact detection (Luu et al., 2011, 2016; Liang et al., 2017). Although the independent component analysis (ICA) becomes popular in artifact removal for the analysis of EEG data and possibly improves the accuracy of the results, the ICA approach is usually required to identify artifact components, following decomposition based on either spatial topographies or temporal characteristics or both, which is a subjective process. As a result, the biased ICA results could be obtained by subjective errors. Moreover, a more serious limitation of using the ICA approach is that it needs a large number of observations (data points) to generate stable independent components (Luu et al. 2016). The ICA approach would be used in future if large data could be collected to get a more accurate result. Further research should consider investigation of associations between visual processing activity and visual detection training in hearing impaired people with and without hearing aids. It would also be useful to understand how the enhancement of visual processing in the auditory associated cortex would affect the rehabilitation outcomes in patients with hearing loss.

Conclusions

The ERP responses in the present study show that adults with hearing loss had a stronger P170 response in the occipital area, as well as higher N2 amplitude but shorter N2 latency in the frontal-temporal area when using 'sound' and 'non-sound' photo stimuli. Further analysis reveals that adults with hearing loss have a large difference in their responses to 'sound' and 'non-sound' photos in the right frontotemporal area, starting from about 200 ms to 400 ms, and that this source was located in the middle

frontal gyrus region (BA10) at around 266 ms. The significantly stronger responses to visual stimuli indicate enhanced visual processing in auditory associated cortex in adults with hearing loss, which may be attributed to cortical visual re-organization involving with right frontotemporal cortex.

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