

Event-related Potentials Reveal Early Visual-tactile Integration in the Deaf*

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This study examined visual-tactile perceptual integration in deaf and normal hearing individuals. Participants were presented with photos of faces or pictures of an oval in either a visual mode or a visual-tactile mode in a recognition learning task. Event-related potentials (ERPs) were recorded when participants recognized real faces and pictures of ovals in learning stage. Results from the parietal-occipital region showed that photos of faces accompanied with vibration elicited more positive-going ERP responses than photos of faces without vibration as indicated in the components of P1 and N170 in both deaf and hearing individuals. However, pictures of ovals accompanied with vibration produced more positive-going ERP responses than pictures of ovals without vibration in N170, which was only found in deaf individuals. A reversed pattern was shown in the temporal region indicating that real faces with vibration elicited less positive ERPs than photos of faces without vibration in both N170 and N300 for deaf, but such pattern did not appear in N170 and N300 for normal hearing. The results suggest that multisensory integration across the visual and tactile modality involves more fundamental perceptual regions than auditory regions. Moreover, auditory deprivation played an essential role at the perceptual encoding stage of the multisensory integration.

Keywords: hearing loss, visual-tactile interaction, perceptual encoding, multisensory integration, event-related potential

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Highlights:

- Multisensory integration across the visual and tactile modality involves more fundamental perceptual regions than auditory regions.
- Auditory deprivation played an essential role at the perceptual encoding stage of the multisensory integration.

In order to form a coherent perception of external stimuli, people usually automatically integrate input from different sensory modalities. For example, when listening to a speech, people tend to look at the speaker's face or eyes, because the face and eyes can convey important information and help better understand the speech (Gurler et al., 2015). This ability, known as multisensory integration, is assessed by the effectiveness of a cross-modal stimulus combination, and has been found to enhance the salience of perceptual events (Ghazanfar et al., 2005; Ghazanfar & Schroeder, 2006; Stein & Meredith, 1993; Stein & Stanford, 2008).

A large body of literature has provided evidence that the presence of redundant information in one modality (e.g., vision and audition) can facilitate target recognition, increase signal-to-noise ratios and reduce reaction times to cross-modal events (Driver & Spence, 1998; Peter et al., 2019), indicating that sensory systems do not function independently but influence each other (Driver & Noesselt, 2008). For example, the famous McGurk effect showed that "ba" was perceived as "da" when one hears the pronunciation of "ba" and sees the mouth shape of pronouncing "ga" simultaneously (McGurk & MacDonald, 1976). Such integration reflects the effect of vision on auditory processing.

Previous neurophysiological studies have even shown the reverse direction that auditory stimuli play an important role in visual perception. For example, Bolognini, Senna, Maravita, Pascual-Leone, and Merabet (2010) found that the auditory effect on visual phosphenes reached a maximal level when auditory stimuli preceded the occipital transcranial magnetic stimulation (TMS) pulse by 40 ms, indicating that auditory stimuli lead to the enhancement of visual cortical excitability, which in turn lead to early audio-visual interaction. That is, the integration between visual and auditory modalities appeared to be bi-directional (Esteve-Gibert & Guellai, 2018). Improved performance in perceptual tasks has also been found in the combinations such as tactile and auditory input as well as tactile and visual input (Driver & Noesselt, 2008; Stein & Stanford, 2008).

Recent studies in deaf people have provided convincing behavioral, electrophysiological and neuroimaging evidence that sensory deprivation in one modality can have a striking effect on the development of the spared modalities (Kalaivani & Ravindran, 2009; Hauthal et al., 2015). For example, previous studies have shown enhanced performance (e.g., faster RTs) of the deaf compared to hearing participants in detecting visual stimuli (Bottari et al., 2011;

Heimler & Pavani, 2014), which contributed to the fact that auditory cortex of the deaf may be recruited to perform visual function. Further studies indicate that deaf children employed a visual encoding strategy to absorb information from the environment, facilitating the allocation of attention to both the central and peripheral visual fields (Bavelier et al., 2000; Rothpletz et al., 2003; Sladen et al., 2005). Additionally, enhanced tactile sensitivity in deaf adults reflects their neural plasticity and increased attention directed to the tactile stimuli, indicating that the auditory cortex of the congenitally deaf was involved when processing tactile information (Levänen & Hamdorf, 2001; Hötting et al., 2004).

However, beyond the effect of auditory deprivation on each of the remaining modalities, very few studies have been conducted on deaf individuals by focusing on the multisensory integration across the spared modalities (e.g., visual and tactile; Bavelier et al., 2006). Specifically, it remains unknown whether the multisensory integration across the remaining modalities is affected by auditory deprivation. A large body of research has provided converging evidence that the deaf showed more activation in the superior temporal sulcus (a typical auditory brain region) than in hearing controls when exposing to visual, tactile and signed input (Bavelier et al., 2001; Beauchamp et al., 2004; Fine et al., 2005; Finney et al., 2003; Levänen et al., 1998; Neville et al., 1998; Petitto et al., 2000). These results are consistent with a cross-modal functional reorganization of the auditory cortex after auditory deprivation (Auer Jr et al., 2007; Levänen et al., 1998).

Up to now, the studies by Karns, Dow, and Neville (2012) and Hauthal et al. (2015) were the only two studies that had focused on the integration of visual and tactile input in deaf people. Karns et al. (2012) showed that single flashes accompanied by two touches were perceived as double flashes by the deaf instead of the normal hearing participants. Following Karns et al.'s study (2012), Hauthal et al. (2015) presented visual, tactile, and visuo-tactile stimuli to congenitally deaf and hearing individuals in a speeded detection task (i.e., participants were asked to make a speeded response to each stimulus irrespective of the sensory modality with the duration of the visual stimulus being 50 ms and the tactile stimulus 45 ms). They found a reverse result pattern that multisensory interaction between the visual and tactile modalities was present in both deaf and hearing groups and was more pronounced in the hearing than in the deaf.

On one hand, as Hauthal et al. (2015) used a speeded detection task, their results were thus possibly confounded by the speeded response of participants as noted in Liu et al. (2012). On the other hand, there were potential baseline differences in manual responses between the deaf and hearing individuals. For example, Poizner (1983) found that deaf and hearing individuals significantly differed in their patterns of dimensional salience for movements at the lexical and inflectional levels. Gkouvatzis, Mantis, and Kambas (2010) even showed important differences in visual-motor control between two groups of hearing-impaired subjects (i.e., deaf and hard-of-hearing) by demonstrating a significant interaction between the subjects and age group categories.

Based on such a situation, the visual-tactile integration in deaf individuals should be revisited with better control. Firstly, as the speeded response may confound the main effect of interest (Liu et al., 2012), the current study only focused on the learning stage without any manual response. Such manipulation could reduce the confounding effect from motor responses on the ERP waveforms. In addition, the problem of different baselines in manual responses between the deaf and hearing can be avoided. Secondly, it has been found that visual systems are highly adapted to the visual properties conveyed by complex stimuli, and the brain's response to such complex stimuli can't be fully understood through the use of simple stimuli (Kayser et al., 2004; Rousselet et al., 2002).

The findings of both Karns et al. (2012) and Hauthal et al. (2015) were only based on simple visual stimuli (i.e., flash and white disk). The current study investigated how the complexity of visual stimuli (i.e., real face vs. oval picture) modulated the coactivation mechanism of visual-tactile processing in deaf people. Face is used in the present study as face recognition is unique in the sense of relying on functionally and anatomically distinct mechanisms from those required for other kinds of pattern recognition (Sergent et al., 1992). Additionally, facial muscle fibers insert directly into the skin rather than the connective tissue, allowing embedded mechanoreceptors to encode information about changes in muscle length and force (Venkatesan et al., 2014). Thus, face perception would be affected by vibrotactile information.

Another important issue to be addressed is the processing stage in which the visual-tactile integration occurs. Previous studies focusing on the interaction between audition, vision, and touch showed that the visual-auditory and visual-tactile integration could occur at an early stage of processing (usually about 200 ms). For example, Hauthal et al. (2015) compared evoked neural dynamics of unisensory visual and tactile stimuli to synchronous visuotactile stimulation. The latency of the tactile N200 component (152–252 ms after stimulus presentation) was modulated by a simultaneous presentation of a visual stimulus in normal hearing but not early deaf. Kennett et al. (2001) found that the visual N1 component (160–200 ms post stimulus onset) was enhanced when tactile stimulation occurred at the same location as the visual event. However, results in Li and Wu's (2008) study showed that audio-visual integration was not found during early sensory processing phase, but was found firstly over central scalp around 300 ms. Thus, it is still unclear whether multisensory integration based on complex stimuli can occur in early perceptual processes.

The present study was intended to investigate the two aforementioned issues: whether the complexity of stimuli (photo of real face vs. oval picture) plays a role in the early perceptual stage (around 200 ms) of visual-tactile integration in the deaf and if so how. Electrophysiological methods, such as event-related potentials with high temporal resolution, can provide more neural dynamic information about brain activities than behavioral and neuroimaging methods, allowing accurate analysis of different cognitive processes (Kutas et al., 2006). Thus, the present study employed the ERPs technique to address the above issues by focusing on the early components P1 and N170 as well as the

late component N300. There is evidence that P1 is sensitive to the first- and second-order configuration of a face (e.g., Cassia et al., 2006). Previous literature also suggests that the N170 component is modulated by face processing (e.g., Liu et al., 2016). We analyzed the impact of the stimulus (photo of real face vs. oval picture), vibration (vibration trial vs. no-vibration trial), and group (early deaf individuals vs. normal hearing individuals) conditions on the amplitude of the P1 and N170 components. As the N300 is sensitive to semantic processing (e.g., Yum et al., 2011), it was also studied to find if these factors could affect post-perceptual processes similar to Mercure, Dick, and Johnson (2008).

Two groups of participants (i.e., a deaf sample and a corresponding normal hearing sample) were recruited to pin down the effect of auditory deprivation on the spared sensory systems. Both simple and complex stimuli (i.e., pictures of white ovals and photos of real faces) were employed to explore whether there would be any difference in visual-tactile processing between simple and complex stimuli. The selection of oval pictures as simple visual stimuli and photos of real faces as complex stimuli is because the picture of an oval is a part of the face picture (see Figure 1).

Due to the higher vibrotactile sensitivity of the photo of real face, we predict that the visual-tactile processing is more pronounced in real face photo relative to oval picture. In addition, it was also investigated whether there would be any difference concerning visual-tactile processing in the course of the perception of the stimuli between the deaf and normal hearing individuals. Greater recruitment in the superior temporal sulcus has been reported to emerge in the deaf rather than in normal hearing individuals when exposed to visual, tactile, and signed input (Bavelier et al., 2001; Fine et al., 2005; Levänen et al., 1998; Neville et al., 1998; Petitto et al., 2000). Therefore, the current study investigates what would happen in both visual and auditory areas as opposed to the concentration on the visual area by Hauthal et al (2015), and expected more pronounced visual-tactile integration in the deaf than the hearing.

Methods

Participants

Deaf Sample

Twenty-one deaf undergraduate students (13 males, $M \pm SD = 21.76 \pm 1.22$ years) from College of Municipal Works and Construction (Guangdong, China), with early hearing loss onset (0–3 years), took part in this experiment. All were right-handed native Chinese Sign Language (CSL) signers and had a binaural hearing loss of 90 dB or above for the better ear which was measured by pure tone audiometry (average at 0.5, 1, and 2 kHz). Handedness was assessed by the Edinburgh Inventory (Oldfield, 1971). All had normal or corrected-to-normal vision, and none of them had any additional handicap or cochlear implantation.

Normal Hearing Sample

Twenty-two hearing undergraduate students (10 males, $M \pm SD = 21.41 \pm 1.56$ years) from South China Normal University and South China University of Technology (Guangdong,

China) took part in this experiment. All were right-handed as assessed by the Edinburgh Handedness Inventory, and had normal or corrected-to-normal vision with an average auditory threshold lower or equal to 20 dB (pure-tone average at 0.5, 1, and 2k Hz). None of them had any knowledge about the Chinese Sign Language (CSL).

All participants gave informed consent and were paid for their participation, none had played any action video games (enhancement in visual attention for habitual action video game players have been reported; Dye et al., 2009). The study was approved by the Institutional Review Board of the South China Normal University (Guangzhou, China) and carried out in accordance with the Declaration of Helsinki principles.

Instruments

The face stimuli consisted of 198 neutral photos of real faces (99 male real faces photos) from the Chinese Affective Face Picture System* (CAFPS; Luo et al., 2009; Wang & Luo, 2005), which has been standardized for mainland Chinese participants. 108 of the photos of real faces (54 male real faces photos) were further morphed in the eye or nose with Adobe Photoshop CS® software (54 with altered eye and 54 with altered nose), and paired with their original photos of real face resulting in 108 incongruent sets of real faces. 90 of photos of real faces (45 male photos of real faces) were paired with themselves, resulting in 90 congruent sets of photos of real faces. One of the two photos of real faces in a set was present in the learning stage, the other appeared in the recognition stage. We counterbalanced the presentation order of original real face and morphed real face of an incongruent set in the learning stage and the recognition stage across participants.

The 198 sets of photos of real faces were divided into two lists with each including 54 incongruent sets of photos of real faces and 45 congruent sets of photos of real faces. The learned photos of real faces (i.e., 99 real faces) in one list were paired with a vibration tactile stimulus at a frequency of 60 Hz, while the learned photos of real faces in another list was not. A weak tactile stimulation was chosen as shown by Senkowski et al. (2011) and Hauthal et al. (2015) that multisensory integration is more likely to occur in response to stimuli with low intensity. The rest of the photos of real faces (i.e., 99 real faces) in one list were presented in recognition stage. Thus, four conditions of photos of real faces were created: Learned Faces with Vibration (LF+V condition), the Learned Faces without Vibration (LF-V condition), the Recognized Faces in Vibration trial (RF+V condition), and the Recognized Faces in Non-vibration trial (RF-V condition). The four lists were balanced for subjective familiarity (means being 2.39, 2.31, 2.39, and 2.37 for the LF+V, LF-V, RF+V, and RF-V real faces respectively, $F < 1$), subjective pleasantness ratings (means being 2.80, 2.78, 2.74, and 2.67 for the LF+V, LF-V, RF+V, and RF-V real faces respectively, $F < 1$), and subjective harmony ratings (means being 3.19, 3.18, 3.21, and 3.10 for the LF+V, LF-V, RF+V, and RF-V real faces respectively, $F < 1$).

Familiarity, pleasantness, and symmetry ratings were obtained from 19 hearing participants from the same subject pool who did not contribute to the ERP data. They were asked to rate the familiarity, pleasantness, and symmetry of the real faces based on a 7-point Likert scale with 1 for least familiar, pleasant, or symmetrical and 7 for most familiar, pleasant, or symmetrical.

All neutral photos of real faces were presented in the frontal view. A picture of oval mask was used to isolate each photo of real face (see Figure 1) and to discourage the use of a non-face feature. Resulting cropped photos of real faces were converted to a 256 gray-level format, rescaled proportionally to a size of 8.5 cm × 9.6 cm, and equated for mean pixel

* Permission was required.

luminance with Adobe Photoshop CS® software. Two additional sets of photos of real faces (one incongruent set and one congruent set) were created as filler items. A picture of oval-shaped white circle was repeated sixty times serving as baseline were used with half of them paired with vibration (referred to as O+V condition), while the other half were not (referred to as O-V condition).

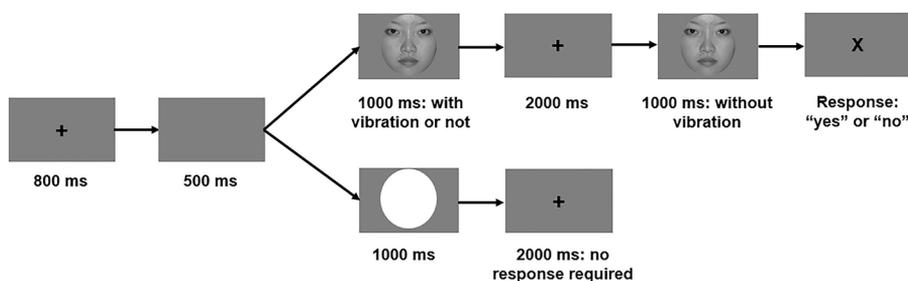
Procedure

Participants were comfortably seated in a quiet and dimly-lit room at a viewing distance of 65cm. Following task instructions and 16 practice trials, they completed three test blocks, each with 88 trials (i.e., 86 test trials with 2 warm-up trials). Learned stimuli were presented in a unisensory visual (e.g., a real face or a picture of white oval) or a bisensory visuo-tactile mode (e.g., a photo of real face or a picture of white oval with vibration). The bisensory stimulation was implemented via the simultaneous presentation of visual and tactile stimuli.

Each trial started with a fixation cross presented in the center of the gray screen for 800ms. After a 500 ms blank screen, a photo of real face or a picture of oval was presented in either a unisensory visual mode or a bisensory visuo-tactile mode. The duration of each test visual stimulus (i.e., a real face or an oval) was 1000 ms. Each tactile stimulus lasted for 1000 ms as well. If it was a real face, then after another fixation cross for 2000ms, a new photo of real face, either a morphed one or the same photo of real face, was presented against the gray background for 1000ms without vibration. Participants determined whether or not the two successive real faces were the same by using the index finger of each hand to press either “Yes” key or “No” key at the sight of the central “X” which was displayed upon the offset of the second real face. If it was an oval picture, a fixation cross for 2000ms appeared and no response was required (see Figure 1).

Figure 1

A flow chart of the task and examples of the stimuli



The first two trials of each test block were fillers. There was a one-minute break between blocks. Participants were allowed to proceed to the test session only if they had achieved at least 75% accuracy in the practice session.

EEG Recording and Analysis

EEGs were recorded from the scalp with a 64-channel Ag-AgCl electrode cap (10–20 system) (EASYCAP GmbH, Steingrabenstrasse 14, DE-82211 Herrsching, Germany; Klem et al., 1999) with sampling rate of 1000 Hz and a band-pass of 0.05–250 Hz. All of the electrodes were referenced on-line to FCz and re-referenced off-line to the mean of the

two mastoids. Monitor eye movements were recorded simultaneously by bipolar horizontal and vertical electro-oculograms. EEG and EOG data were amplified with two 32-channel BrainAmp MR Plus amplifiers (Brain Vision Recorder Version 1.2; Brain Products, Gilching). Electrode impedances were maintained below 5 k Ω throughout the recording session.

Eye movements were corrected using the ocular correction ICA transformation in Brain Vision Analyzer 2.0.4 (Brain Products GmbH, Munich, Germany). Epochs with potentials exceeding $\pm 80\mu\text{V}$ at any cap electrode were rejected automatically. Epochs were measured from -200 to 800 ms time-locked to the onset of the learned and recognized real faces and oval pictures in each trial. ERP amplitude was measured with respect to the average baseline voltage over the interval from -200 to 0 ms.

As the current study primarily looked at the visual-tactile bimodal processing, so electrodes in parietal-occipital scalp including O1, Oz, PO3, PO4, PO7, PO8 and POz were chosen for further analysis. Similar to previous studies (e.g., Hoormann et al., 1998), the time window for each component used in this study was determined after visual inspection of the grand means. For parietal-occipital region, mean ERP amplitudes were calculated off-line for each participant in three components, including P1 (i.e., 120–170 ms for early deaf participants and 100–150 ms for normal hearing participants), N170 (i.e., 170–220 ms for early deaf participants and 150 to 200 ms for normal hearing participants) and N300 (i.e., 270–370 ms for early deaf participants and 250–350 ms for normal hearing participants).

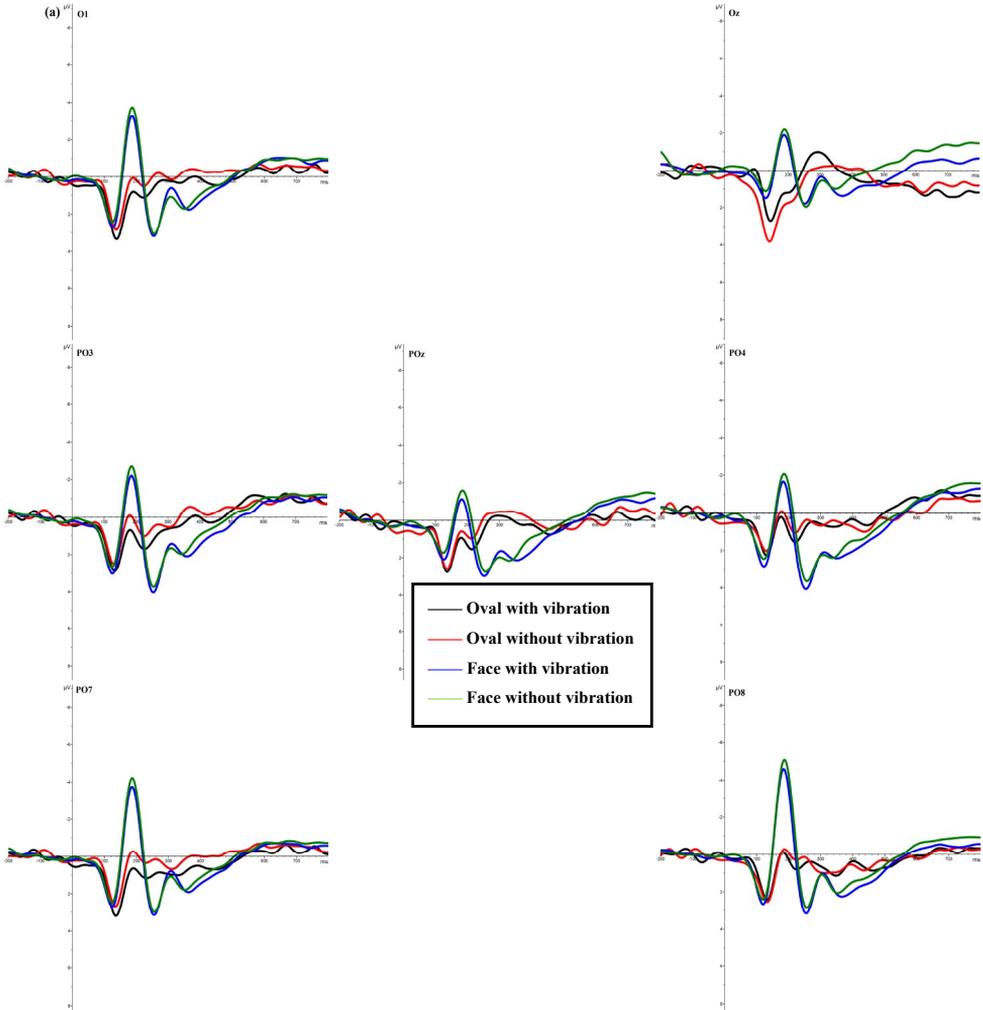
According to the finding that a cross-modal functional reorganization of the auditory cortex occurred following auditory deprivation, electrodes in temporal scalp including FT7, FT8, T7, T8, TP7, and TP8 were also chosen for further analysis. For the temporal region, mean ERP amplitudes were calculated off-line for each participant in N170 (i.e., 140–240 ms for early deaf participants, 120 to 220 ms for normal hearing participants) and N300 (i.e., 240–340 ms for early deaf participants, 220–320 ms for normal hearing participants). Additionally, we separated parietal-occipital and temporal electrode sites in the statistical analyses as parietal-occipital region and temporal region have been associated with different functions.

Results

As the pictures of oval were presented only in the learning stage, the design is not fully symmetrical. The main task was used as a cover task. Therefore, the analysis mainly focused on ERP responses in the learning stage. Grand-averaged ERP waveforms time-locked to stimuli onset for all conditions in the learning stage for deaf (parietal-occipital region: see Figure 2a; temporal region: see Figure 3a) and hearing (parietal-occipital region: see Figure 4a; temporal region: see Figure 5a) are shown with representative electrodes. Three-way repeated-measures ANOVA were conducted with three factors, Stimulus Type (real face vs. oval picture), Vibration Type (vibration trial vs. no-vibration trial), and Group (early deaf individuals vs. normal hearing individuals).

Figure 2

Grand average event-related potentials for all conditions and scalp topographic maps in Parietal-occipital region in learning stage for deaf at representative electrodes



(b) Oval with vibration Oval without vibration Face with vibration Face without vibration

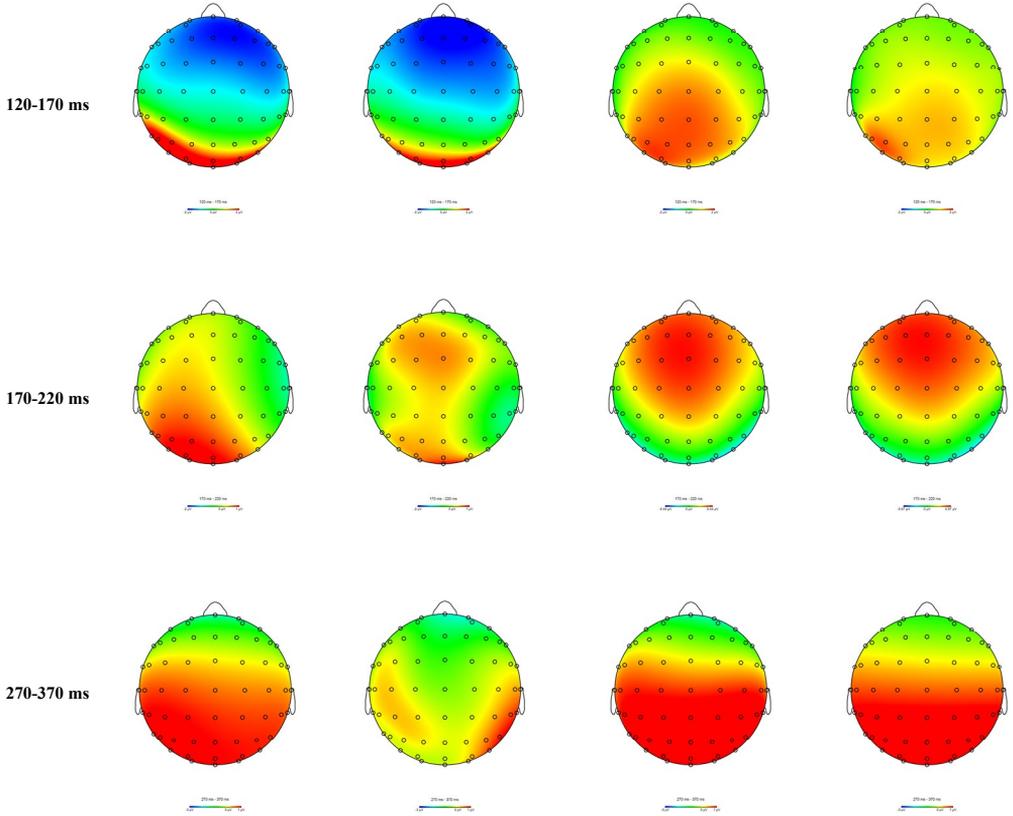


Figure 3

Grand average event-related potentials for all conditions and scalp topographic maps in Temporal region in learning stage for deaf at representative electrodes

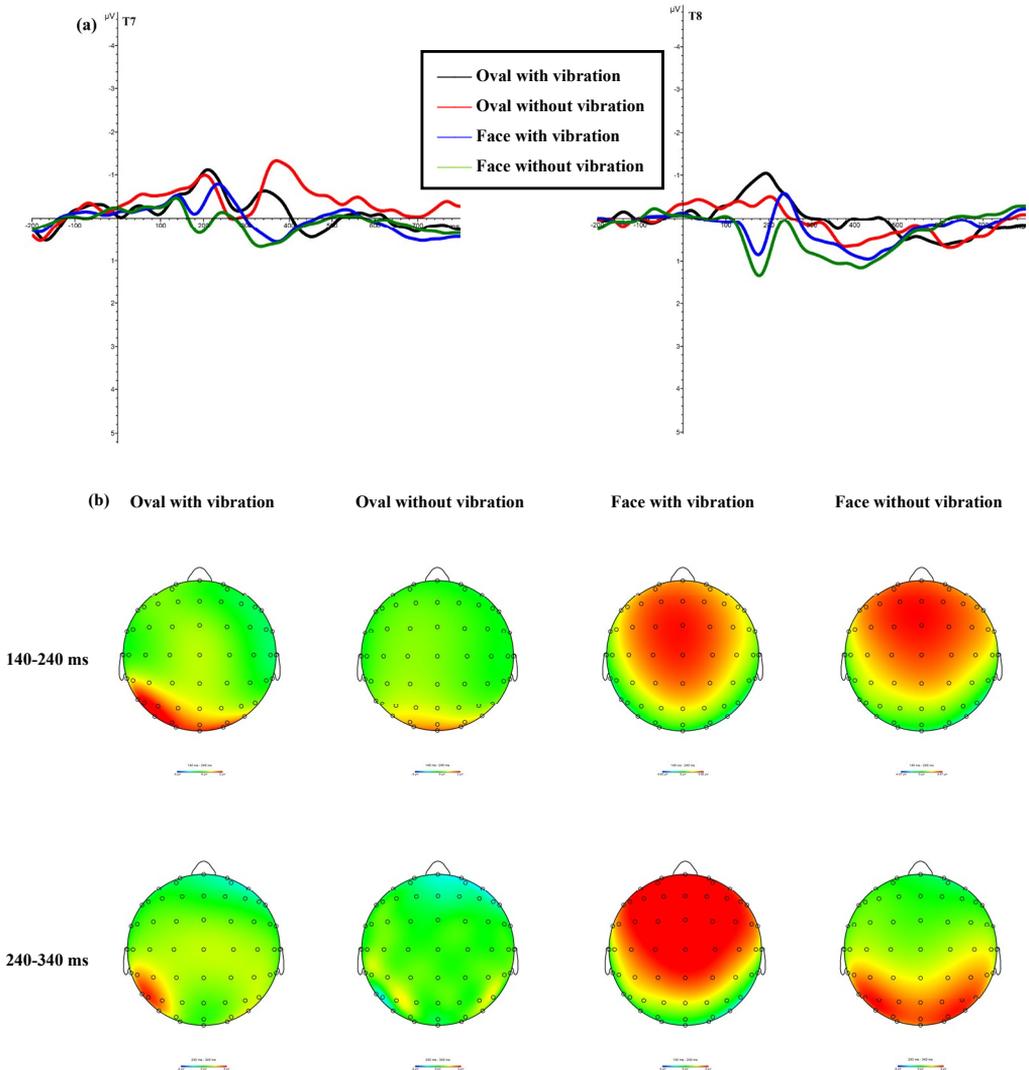
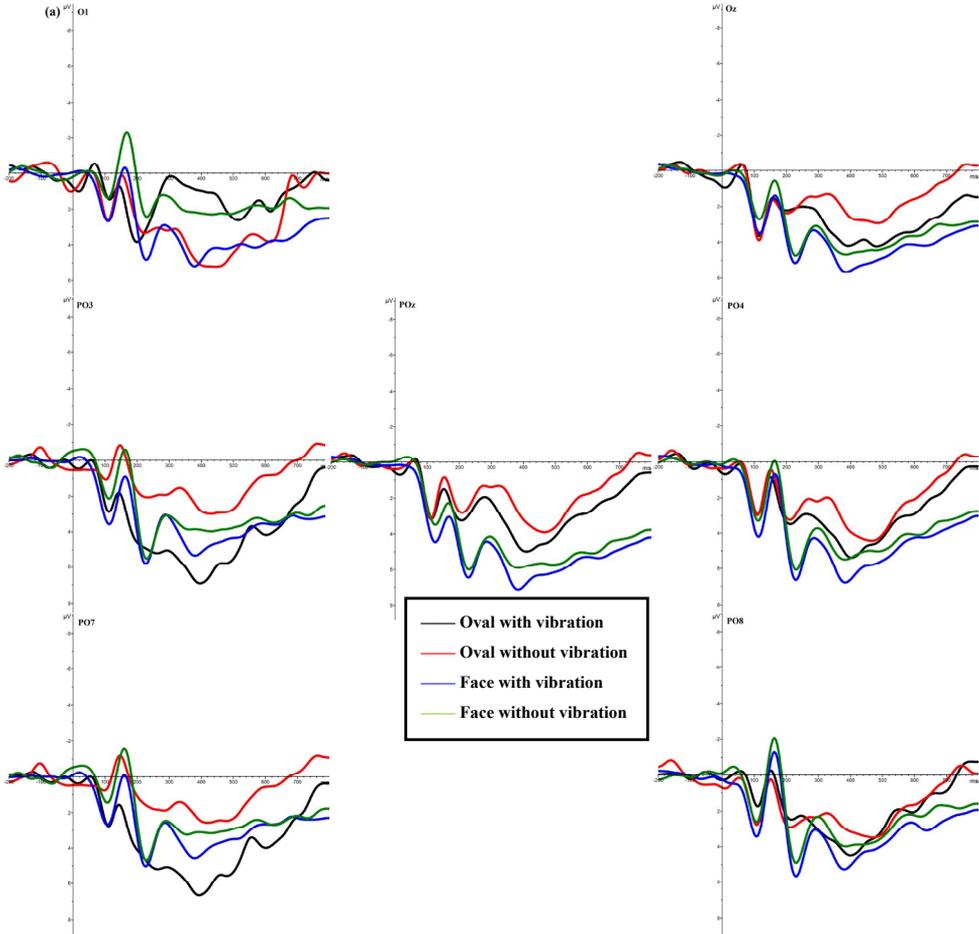


Figure 4

Grand average event-related potentials for all conditions and scalp topographic maps in Parietal-occipital region in learning stage for normal hearing at representative electrodes



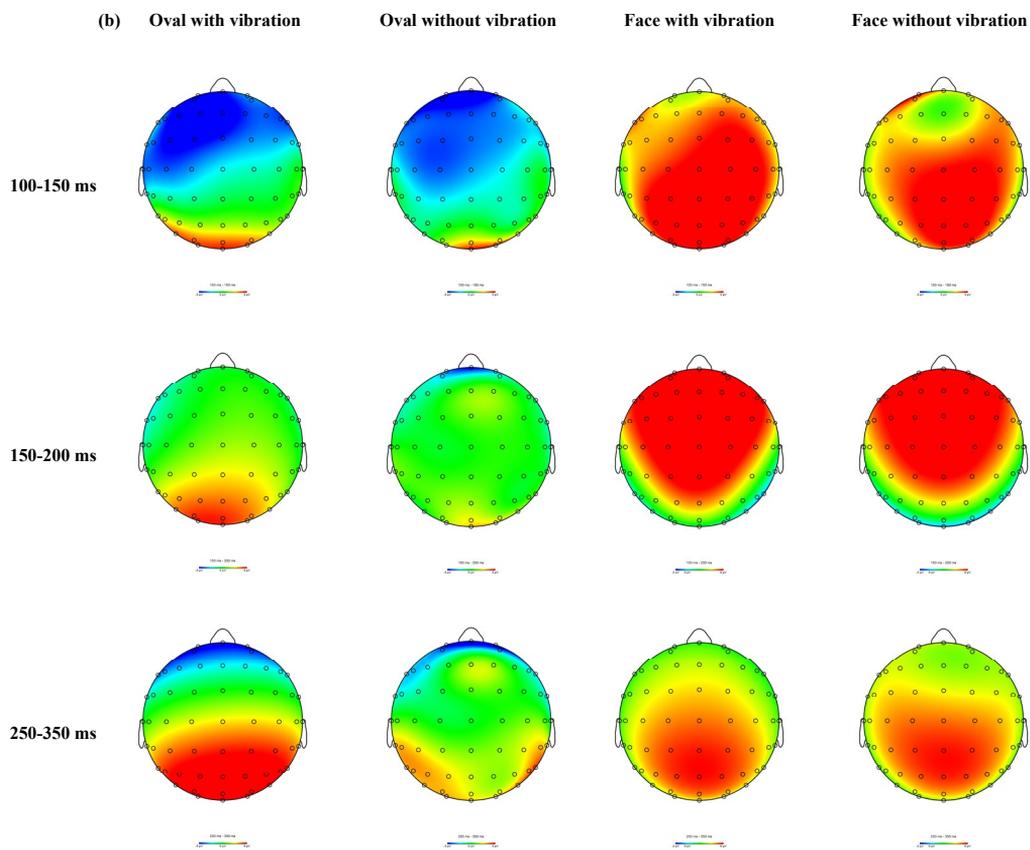
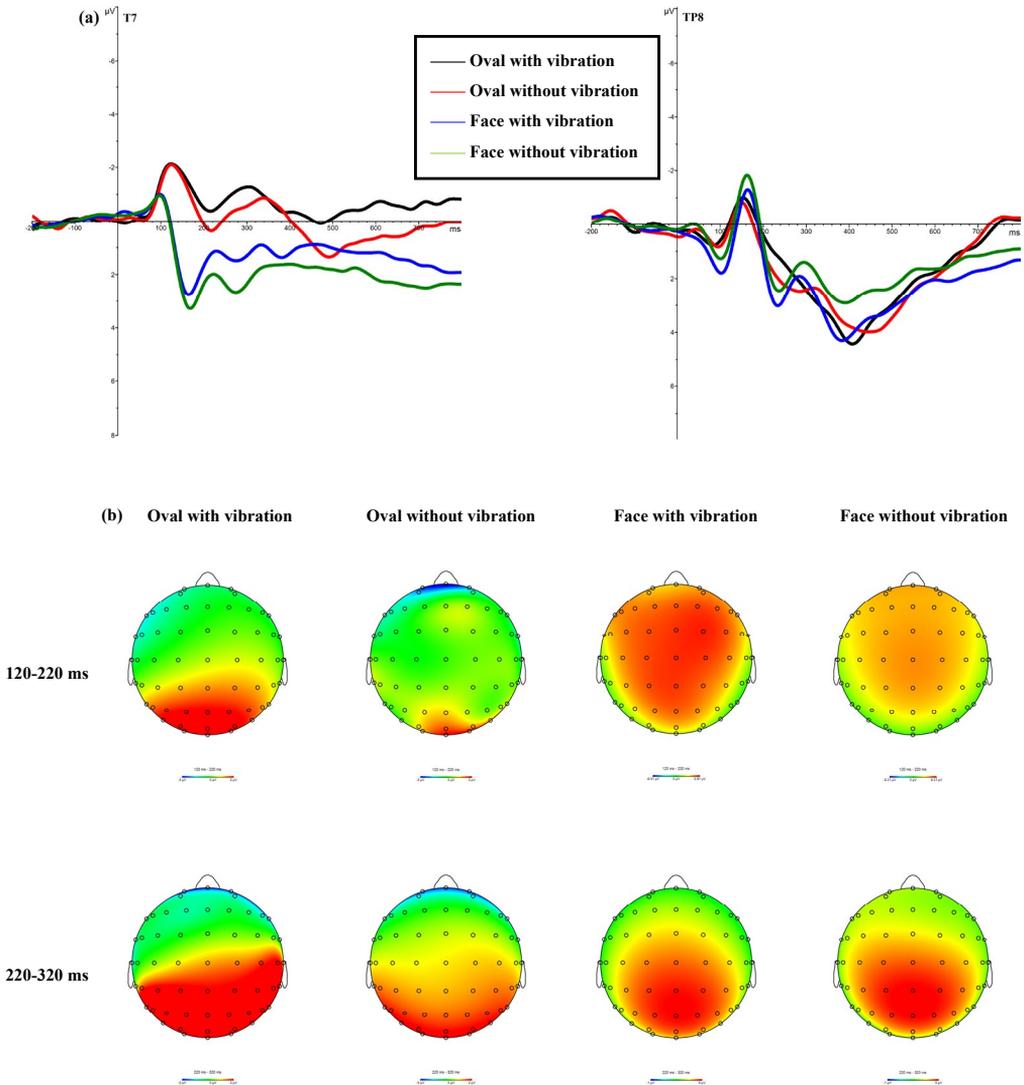


Figure 5

Grand average event-related potentials for all conditions and scalp topographic maps in Temporal region in learning stage for normal hearing at representative electrodes



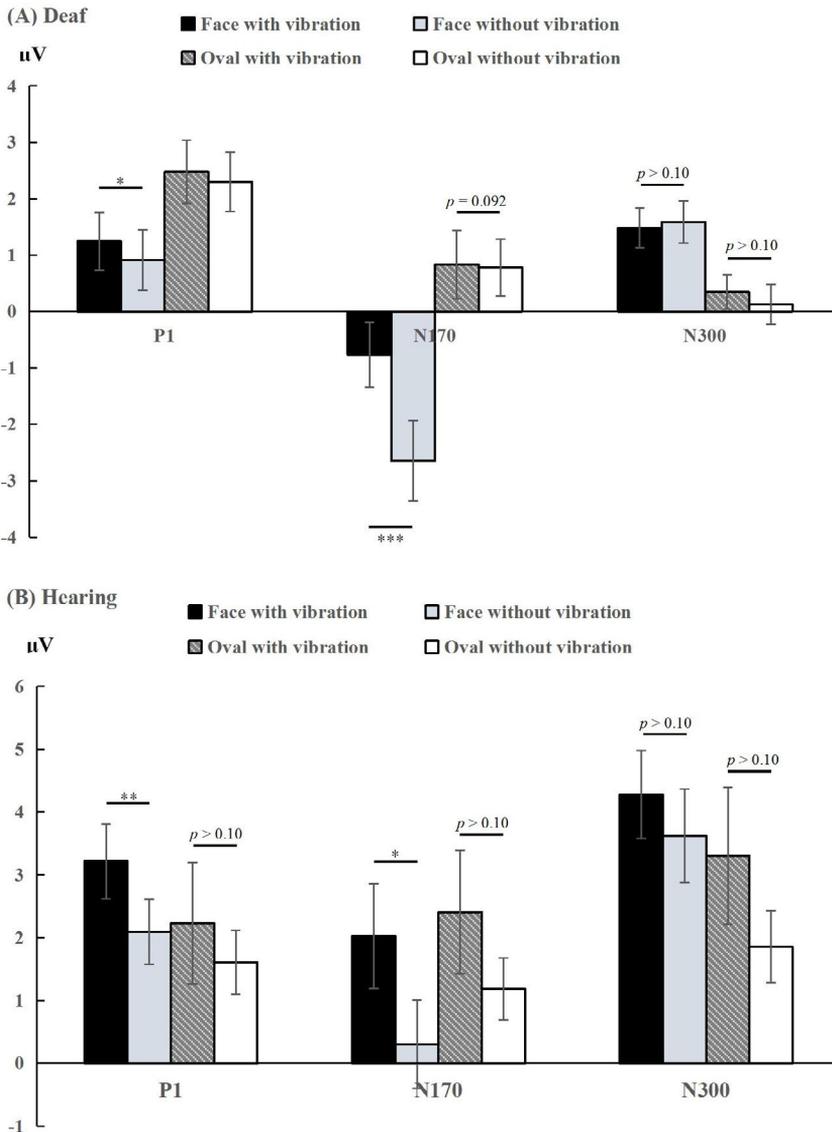
Parietal-Occipital Region (visual region)

Figure 6 shows the mean amplitudes in P1, N170, and N300 for deaf and hearing participants in parietal-occipital region. Figure 2b shows the scalp topographic maps for all the conditions in deaf in P1 (120–170 ms), N170 (170–

220 ms), and N300 (270–370 ms). Figure 4b shows the scalp topographic maps for all the conditions in normal hearing in P1 (100–150 ms), N170 (150–200 ms), and N300 (250–350 ms).

Figure 6

Mean amplitudes are presented for deaf (A, the upper panel) and hearing (B, the lower panel) in all conditions in the learning stage over the Parietal-occipital region. Error bars for standard error to the mean



PI. The three-way ANOVA on mean signal amplitudes showed a significant main effect of Vibration Type, ($F(1, 41) = 3.93, p = .05, \eta_p^2 = .09$) with larger amplitudes in the vibration condition ($2.29\mu\text{V}$) than in the non-vibration condition ($1.73\mu\text{V}$). The interaction between Stimulus Type and Group was significant ($F(1, 41) = 12.43, p < .01, \eta_p^2 = .23$). The results showed less positive-going ERP responses for real faces ($1.08\mu\text{V}$) than for oval pictures ($2.39\mu\text{V}$) in the deaf individuals ($F(1, 20) = 21.51, p < .01, \eta_p^2 = .52$), while they were comparable in the normal hearing individuals (oval vs. real face: $1.92\mu\text{V}$ vs. $2.66\mu\text{V}$; $F(1, 21) = 2.17, p = .16, \eta_p^2 = .09$). The ERPs to real faces produced more positive-going ERP responses for normal hearing individuals ($2.66\mu\text{V}$) than those for deaf individuals ($1.08\mu\text{V}$; $F(1, 41) = 4.58, p = .04, \eta_p^2 = .10$), whereas there was no significant difference in oval condition between the normal hearing ($1.92\mu\text{V}$) and deaf ($2.39\mu\text{V}$) individuals ($F(1, 41) = .30, p = .59, \eta_p^2 < .01$). However, no effect of other two-way interactions nor three-way interaction has been found to be significant ($ps > .10$).

N170. Results in this component showed significant main effects for Stimulus Type ($F(1, 41) = 18.54, p < .01, \eta_p^2 = .31$), Vibration Type ($F(1, 41) = 8.35, p < .01, \eta_p^2 = .17$), and Group ($F(1, 41) = 6.65, p = .01, \eta_p^2 = .14$), with larger negative-going ERP responses for photos of real faces ($-.27\mu\text{V}$) in comparison with that for oval pictures ($1.19\mu\text{V}$), larger negative-going ERP responses for non-vibration condition ($-.20\mu\text{V}$) as opposed to vibration condition ($1.13\mu\text{V}$), and larger negative-going ERP responses for deaf ($-.56\mu\text{V}$) than normal hearing individuals ($1.48\mu\text{V}$). The interaction between Stimulus Type and Group was significant ($F(1, 41) = 6.01, p = .02, \eta_p^2 = .13$). There was larger negative-going ERP responses for photos of real faces than for oval pictures in the deaf individuals ($-1.71\mu\text{V}$ vs. $.59\mu\text{V}$; $F(1, 20) = 21.34, p < .01, \eta_p^2 = .52$), but they were comparable in normal hearing controls ($1.17\mu\text{V}$ vs. $1.80\mu\text{V}$; $F(1, 21) = 1.84, p = .19, \eta_p^2 = .08$). And the amplitude of real faces was larger for the deaf ($-1.71\mu\text{V}$) than that for the persons of regular hearing ($1.17\mu\text{V}$; $F(1, 41) = 9.88, p < .01, \eta_p^2 = .19$), but it was not the case for the oval condition (deaf vs. normal hearing: $.59\mu\text{V}$ vs. $1.80\mu\text{V}$; $F(1, 41) = 2.25, p = .14, \eta_p^2 = .05$). However, the effects of other two-way interactions and three-way interaction were non-significant ($ps > .10$).

N300. Results in this component showed significant main effect for Stimulus Type ($F(1, 41) = 12.99, p < .01, \eta_p^2 = .24$), Vibration Type ($F(1, 41) = 4.06, p = .05, \eta_p^2 = .09$), and Group ($F(1, 41) = 13.01, p < .01, \eta_p^2 = .24$). The photos of real faces ($2.74\mu\text{V}$) elicited more positive-going ERP responses than oval pictures ($1.41\mu\text{V}$). The vibration condition ($2.35\mu\text{V}$) elicited more positive-going ERP responses than the non-vibration condition ($1.80\mu\text{V}$). The normal hearing ($3.26\mu\text{V}$) showed larger positive-going ERP responses than the deaf ($0.89\mu\text{V}$). However, no other interaction effects nor three-way interaction were detected ($ps > .10$).

The amplitude of photos of real faces with vibration (LF+V) and that of real faces without vibration (LF-V) were compared to specifically detect the visual-tactile interaction in the learning stage, which revealed significant vibration effect in the deaf in two early components: P1 (LF+V minus LF-V: $.33\mu\text{V}$; $F(1, 20) = 4.92$, $p = .04$, $\eta_p^2 = .20$), N170 (LF+V minus LF-V: $1.88\mu\text{V}$; $F(1, 20) = 22.79$, $p < .01$, $\eta_p^2 = .53$). Similar vibration effects were also found in the normal hearing participants in the two early components: P1 (LF+V minus LF-V: $1.12\mu\text{V}$; $F(1, 21) = 8.62$, $p < .01$, $\eta_p^2 = .29$), N170 (LF+V minus LF-V: $1.72\mu\text{V}$; $F(1, 21) = 5.13$, $p = .03$, $\eta_p^2 = .20$). The amplitude of learning oval pictures with vibration (LO+V) significantly differed from learning oval pictures without vibration (LO-V) in the deaf in N170 (LO+V minus LO-V: $.48\mu\text{V}$; $F(1, 20) = 3.13$, $p = .09$, $\eta_p^2 = .14$). However, there was no significant difference between LO+V and LO-V in the deaf and normal hearing in any of the three components (all $ps > .10$).

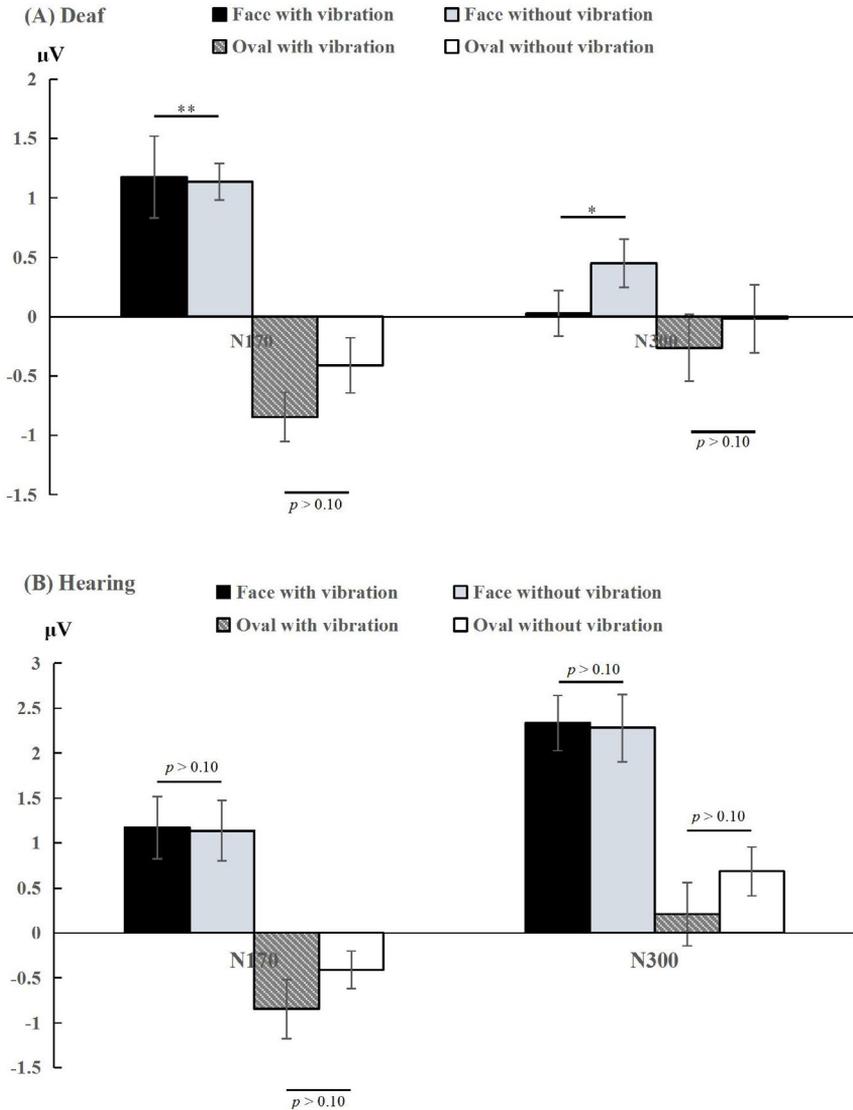
These results suggested that the visual-tactile processing occurs as early as about 120 ms in both deaf and normal hearing participants when the visual stimulus is a real face while it is delayed to about 170 ms when the visual stimulus is an oval picture in the deaf, but no such visual-tactile processing has been found in the normal hearing participants. Our results also showed that photos of real faces elicited larger N170 in deaf than normal hearing adults, which provides evidence to support the notion that deafness can affect processing of visual information in the visual periphery, as well as the neural substrates for these domains (e.g., Heimler & Pavani, 2014).

Temporal Region (Auditory Region)

Figure 7 presents the summarized results in N170 and N300 for deaf and hearing participants over temporal region. Figure 3b shows the scalp topographic map for all the conditions in deaf in N170 (140–240 ms) and N300 (240–340 ms). Figure 5b shows the scalp topographic map for all the conditions in hearing in N170 (120–220 ms) and N300 (220–320 ms).

Figure 7

Mean amplitudes are presented for deaf (A, the upper panel) and hearing (B, the lower panel) in all conditions in the learning stage over the Temporal region. Error bars for standard error to the mean



N170. The results showed significant main effect of Stimulus Type ($F(1, 41) = 80.25, p < .001, \eta_p^2 = .66$), Vibration Type ($F(1, 41) = 4.60, p = .04$,

$\eta_p^2 = .10$) and Group ($F(1, 41) = 3.44, p = .07, \eta_p^2 = .08$). The photos of real faces ($.66\mu\text{V}$) produced more positive-going ERP responses than oval pictures ($-.67\mu\text{V}$). The vibration condition ($-.15\mu\text{V}$) elicited more negative-going ERP responses than the non-vibration condition ($0.14\mu\text{V}$). The normal hearing ($.26\mu\text{V}$) showed larger positive-going ERP responses than the deaf ($-.28\mu\text{V}$). The interaction between Stimulus Type and Group was significant ($F(1, 41) = 9.46, p < .01, \eta_p^2 = .19$). Smaller amplitude was found in the deaf ($.15\mu\text{V}$) relative to the normal hearing ($1.16\mu\text{V}$) in the real face condition ($F(1, 41) = 7.72, p < .01, \eta_p^2 = .16$) while the difference between the two groups was not significant in the oval condition (deaf vs. normal hearing: $-.71\mu\text{V}$ vs. $-.63\mu\text{V}$, $F(1, 41) = .09, p = .77, \eta_p^2 < .01$). No main effect of Group and Vibration Type nor other interaction effect were detected ($ps > .10$).

N300. Similar to *N170*, the results showed significant main effect of Stimulus Type ($F(1, 41) = 34.65, p < .01, \eta_p^2 = .46$) with more positive amplitude in photos of real faces ($1.27\mu\text{V}$) over ovals pictures ($.15\mu\text{V}$), Vibration Type ($F(1, 41) = 3.67, p = .06, \eta_p^2 = .08$) with more negative-going ERP responses in vibration condition ($.58\mu\text{V}$) than non-vibration condition ($.85\mu\text{V}$), and Group ($F(1, 41) = 18.63, p < .01, \eta_p^2 = .31$) with more positive-going ERP responses in normal hearing ($1.38\mu\text{V}$) than the deaf ($.05\mu\text{V}$). The interaction between Stimulus Type and Group was significant ($F(1, 41) = 15.15, p < .01, \eta_p^2 = .27$). Larger amplitude was found in the normal hearing ($2.31\mu\text{V}$) than the deaf ($.24\mu\text{V}$) in the real face condition ($F(1, 41) = 30.40, p < .01, \eta_p^2 = .43$) while the difference between two groups was not significant in the oval condition (deaf vs. normal hearing: $-.14\mu\text{V}$ vs. $-.45\mu\text{V}$, $F(1, 41) = 2.85, p = .10, \eta_p^2 = .07$); Larger amplitude was found for photos of real faces ($2.31\mu\text{V}$) than oval pictures ($.45\mu\text{V}$) in normal hearing individuals ($F(1, 41) = 40.15, p < .01, \eta_p^2 = .66$). There was neither significant main effect of Group and Vibration Type nor any other interaction effect ($ps > .10$).

In order to further reveal the effect of vibration on visual processing. For the deaf, a significant effect of vibration on real face processing was found in both *N170* and *N300* (*N170*: LF+V minus LF-V is $-.49\mu\text{V}$, $F(1, 20) = 9.99, p < .01, \eta_p^2 = .33$; *N300*: LF+V minus LF-V is $-.42\mu\text{V}$, $F(1, 20) = 7.08, p = .02, \eta_p^2 = .26$). For the normal hearing, there was not a significant effect of vibration on real face photo processing in *N300* (LF+V minus LF-V is $.05\mu\text{V}$, $F(1, 21) = .05, p = .82, \eta_p^2 < .01$) and *N170* (LF+V minus LF-V is $-.04\mu\text{V}$, $F(1, 21) = .03, p = .88, \eta_p^2 < .01$). However, there is no significant effect of vibration on oval picture processing in either *N170* or *N300* for either the deaf or the normal hearing (all $ps > .10$). These results suggested that the auditory area was also involved in visual-tactile processing in both early deaf and normal hearing participants only when the visual stimuli is a complex real face. Additionally, the visual-tactile processing for complex stimuli seems to start earlier in the early deaf than in the hearing participants.

Discussion

The present study examined the visual-tactile integration in deaf and normal hearing participants by using simple and complex visual stimuli, in the hope of specifying the effects of stimulus complexity and group on the neural underpinnings of visual-tactile integration. Results concerning the parietal-occipital region showed that in P1 and N170 real faces photos accompanied with vibration in the learning stage produced more positive-going ERP responses than real faces photos without vibration in both deaf and normal hearing. However, oval pictures accompanied with vibration produced more positive-going ERP responses than oval pictures without vibration only in deaf in the components of N170. Results concerning the temporal region showed the reversed pattern that real faces accompanied with vibration elicited less positive-going ERP responses than those without vibration in the components of N170 and N300 in deaf, but such pattern not appeared in N170 and N300 for normal hearing.

Results in the parietal-occipital region suggest that visual-tactile bimodal processing of complex visual stimuli occurs at the perceptual stage for both deaf and normal hearing individuals. Importantly, deaf participants have an advantage in the bimodal perceptual processing of simple visual stimuli as compared with hearing participants. That is, the current study did not find an advantage in visual-tactile processing in deaf individuals when using complex visual stimuli. More importantly, it showed that there is an advantage in visual-tactile processing in the deaf when simple visual stimuli were used. These findings are partially consistent with those of Hauthal et al. (2015) that there were multisensory interactions in both the deaf and hearing groups, but differed in that Hauthal et al. (2015) showed a weaker visual-tactile integration in the deaf.

Our results are also consistent with other previous studies in that the deaf responded faster to simple visual stimuli than the normal hearing individuals did (Bottari et al., 2010; Heimler & Pavani, 2014), suggesting auditory deprivation improves the sensory perception of particular stimuli in deaf individuals. Recently, Iversen et al. (2015) showed that deaf individuals performed better than hearing individuals when synchronizing with visual flashes, indicating there is enhanced cross-modal plasticity between the visual and auditory modalities in the deaf as compared with the hearing. Karns et al. (2012) also showed similar enhanced cross-modal plasticity between visual and somatosensory modalities in primary auditory cortex existed only in the congenital and profound deaf people.

The current study further confirmed the presence of enhanced cross-modal plasticity between visual and somatosensory modalities in deaf individuals. Our results were consistent with most of the previous studies across subjects, sessions, and sensory stimulus setups (Stropahl et al., 2017). However, this study extended the finding of Karns et al. (2012) in that auditory deprivation could exert the effect of cross-modal plasticity on simple visual system even for those non-congenital deaf whose deafness begins at the age of around two. Moreover, the present findings suggested that auditory deprivation has a stimulus-feature dependent underpinning in the processing between visual and somatosensory modalities.

Takeshima and Gyoba (2013) also found that the effect of perceptual efficiency on fission illusion (i.e., when a single flash is accompanied by 2 or more beeps, it is perceived as multiple flashes) varied across different visual patterns in the degree of complexity. Simple visual stimuli (such as flashes or pictures of white ovals) have less meaning and involve less working memory than complex visual stimuli (such as real faces), so deaf people are more likely to enhance cross-modal plasticity during low levels of multimodal processing. Additionally, no explicit task about the oval stimuli was assigned, which resulted in participants would pay less attention to them than the face stimuli. Some previous studies showed that multisensory stimuli were more effectively integrated when the unisensory responses are relatively weak (Diederich & Colonius, 2004; Rach et al., 2011; Hauthal et al., 2015; Senkowski et al., 2011), known as inverse effectiveness theory. Combined with these findings, our results shed light on the fact that auditory deprivation plays a role in magnifying the inverse effectiveness.

Additionally, one notable finding of the present study is that the visual sensitivity of complex stimuli was enhanced in both the deaf and normal hearing group when the visual stimuli were accompanied with a tactile stimulus. Such results are consistent with other evidence showing that the fission illusion was also observed in the hearing (Lange et al., 2011; Violentyev et al., 2005). The results suggest that the cross-modal plasticity of complex visual processing in hearing could reach the same level as that of deaf people aged around 20 years. However, for the deaf, the cross-modal plasticity advantage of simple visual processing continues into adulthood.

The current study found that not only parietal cortex but also temporal cortex plays an important role in visual-tactile processing. Previous cell recordings, tracing work, and neuroimaging studies (Driver & Noesselt, 2008; Stein & Stanford, 2008) strongly indicate that the parietal cortex receives converging feedforward projections from visual, auditory, and somatosensory areas merging incoming information for object recognition and attentional orienting (van Atteveldt et al., 2014). Similarly, James et al. (2002) reported that visual cortex was involved in tactile processing. Recently, Karns et al. (2012) found that both deaf and hearing individuals increased signals in Heschl's gyrus and superior-temporal cortex for visual-somatosensory bimodal stimuli and visual unimodal stimuli and larger responses were found among the deaf than the hearing. Such cross-modal integration in auditory cortex has also been found in previous animal studies. For example, early deaf cats' anterior auditory field was activated by somatosensory cues and visual stimulation (Meredith et al., 2011). Lomber, Meredith, and Kral (2010) reported a causal relationship between the activation of auditory cortex and enhanced performance on visual motion stimuli in deaf-cats. The present results are consistent with the central message from these studies and further indicate the early involvement of parietal cortex and temporal cortex in visual-somatosensory bimodal integration by demonstrating that the greater responses of visual-tactile bisensory in the auditory area appeared as early as around 200 ms in deaf individuals and around 300 ms in normal hearing individuals after the onset of visual stimuli.

Although our findings suggest meaningful insights, the study had limitations that must be addressed in future research. First, the deaf and hearing samples are matched only in that both of them are university students. From the fact that linguistic labels are activated rapidly and influence early visual processing (e.g., Mo et al., 2011), future studies should directly measure participants' linguistic competency to ensure that the deaf who use sign language have similar linguistic competency to the hearing who use spoken language. It is also noteworthy that the Stimulus Type×Vibration Type×Group three-way interaction was not significant in the current study. Still, the main manipulation was between real faces with vibration and those without vibration as well as between oval pictures with vibration and those without vibration in deaf and normal hearing. The non-significant three-way interaction would shed light on that the visual-tactile integration is a weak effect that may be difficult to detect with a between-subject design. Future studies should employ more sensitive methods to collect data. Finally, the study only focused on the online visual-tactile integration. Future studies could take a look at its long-term effect, such as whether the multisensory integration would have an effect on memory.

To conclude, in line with previous findings, results of the present study indicate that parietal cortex and temporal cortex are involved in the early stage of visual-somatosensory bimodal processing in both deaf and normal hearing individuals. Moreover, present results show that enhanced visual-somatosensory plasticity in the deaf is only present in simple rather than complex visual stimuli. This is the first study demonstrating the early involvement of both visual and auditory regions in visual-somatosensory bimodal integration, as well as the enhanced bimodal integration of simple rather than complex visual stimuli in deaf people. It suggests that the multisensory processing across visual and tactile modality involves more fundamental perceptual regions than expected (e.g., auditory region). Additionally, auditory deprivation plays an essential role at the basic level of this bimodal processing especially at the perceptual encoding stage.

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Događajem evocirani potencijali otkrivaju rane vizeulno-taktilne integracije kod gluvih

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U ovoj studiji je ispitivana vizuelno-taktilna preceptivna integracija kod gluvih i kod osoba normalnog sluha. Ispitanicima je predstavljena fotografija lica ili slika ovala u vizuelnom ili vizuelno-taktilnom režimu u zadatku učenja prepoznavanja. Događajem evocirani potencijali (eng. Event-related potentials; ERPs) su beleženi kada bi ispitanici prepoznali sliku lica ili ovala u fazi učenja. Snimci iz parijetalno-okcipitalne regije pokazuju da se slike lica praćene vibracijom bolje prepoznaju nego slike lica koje nisu praćene vibracijom, što je indikivano komponentama P1 i N170 i kod gluvih i kod osoba sa normalnim sluhom. Međutim, slike ovala praćene vibracijom se bolje prepoznaju nego slike ovala koje nisu praćene vibracijom u regiji N170 samo kod gluvih osoba. Obrnuti obrazac je utvrđen u temporalnoj regiji ukazujući da slike lica praćene vibracijom izazivaju manje pozitivnih događajem evociranih potencijala nego slike lica koje nisu praćene vibracije u obe regije za gluve (N170 i N300), ali se ovaj obrazac nije pojavio u istoimenim regijama kod ispitanika normalnog sluha. Rezultati ukazuju da multisenzorna integracija kroz vizuelni i taktilni modalitet uključuje fundamentalnije preceptivne regije nego što su to auditorne regije. Takođe, auditivna deprivacija ima esencijalnu ulogu u fazi preceptivnog kodiranja tokom multisenzorne integracije.

Ključne reči: gubitak sluha, vizuelno-taktilna interakcija, preceptivno enkodiranje, multisenzorna integracija, događajem evocirani potencijali

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