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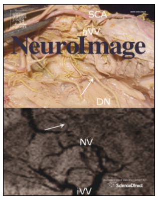

Cross-modal reorganization in cochlear implant users: Auditory cortex contributes to visual face processing

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ABSTRACT

There is converging evidence that the auditory cortex takes over visual functions during a period of auditory deprivation. A residual pattern of cross-modal take-over may prevent the auditory cortex to adapt to restored sensory input as delivered by a cochlear implant (CI) and limit speech intelligibility with a CI. The aim of the present study was to investigate whether visual face processing in CI users activates auditory cortex and whether this has adaptive or maladaptive consequences. High-density electroencephalogram data were recorded from CI users ($n = 21$) and age-matched normal hearing controls ($n = 21$) performing a face versus house discrimination task. Lip reading and face recognition abilities were measured as well as speech intelligibility. Evaluation of event-related potential (ERP) topographies revealed significant group differences over occipito-temporal scalp regions. Distributed source analysis identified significantly higher activation in the right auditory cortex for CI users compared to NH controls, confirming visual take-over. Lip reading skills were significantly enhanced in the CI group and appeared to be particularly better after a longer duration of deafness, while face recognition was not significantly different between groups. However, auditory cortex activation in CI users was positively related to face recognition abilities. Our results confirm a cross-modal reorganization for ecologically valid visual stimuli in CI users. Furthermore, they suggest that residual takeover, which can persist even after adaptation to a CI is not necessarily maladaptive.

1. Introduction

It is known that sensory-deprived brain regions do not remain inactive but that missing unimodal sensory input results in cortical changes (Merabet and Pascual-Leone, 2009). Recent work on visual and auditory deprivation showed converging evidence of cross-modal reorganization after a time of deprivation. In the case of human deafness, the auditory cortex seems to take over visual functions (Finney et al., 2003; Finney et al., 2001; Karns et al., 2012) and this take-over has been related to enhanced visual abilities (Bavelier et al., 2000; Bavelier et al., 2006; Hauthal et al., 2013; Lomber et al., 2010). Cross-modal plasticity can have adaptive and maladaptive effects (Heimler et al., 2014) and may therefore influence the degree of auditory rehabilitation with a cochlear implant (CI).

Previous studies have shown that not only the developing brain (Sharma et al., 2005; Sharma et al., 2007) but also the mature brain of middle-aged (35–62 years) and elderly CI recipients (74–78 years) rapidly adapts to the partly restored (electrical) input within the first weeks after initial implant use (Sandmann et al., 2014). This adaptation process may partly indicate a reversal of deafness-induced loss of functional specialization (Giraud et al., 2001; Pantev et al., 2006; Sandmann et al., 2014; Sharma et al., 2007), and partly reflect the adaptation to the coarse, artificial input as provided by a CI. However, the performance level in hearing and speech comprehension varies strongly among CI users. This suggests differences in the capacity of the auditory cortex to adapt to the electrical input signal after implantation. Pre- and post-surgical factors are known to influence the individual benefit of the CI, among them the onset of hearing loss, the duration of deafness, the extent of residual hearing and CI experience (Blamey et al., 1996,

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2012; Lazard et al., 2012; Petersen, Gjedde, Wallentin, & Vuust, 2013). Thus, the success of the rehabilitation process by a CI seems to depend on the patient's individual conditions, and cortical reorganization and adaptation patterns may help explaining individual differences in CI outcome.

The experience of auditory deprivation is thought to induce a visual take-over type of reorganization in the auditory cortex which is not completely reversed after implantation. Insufficient adaptation to the new input may be reflected by residual signs of visual take-over (Doucet et al., 2006; Lee et al., 2001; Sandmann et al., 2012). Accordingly it was found that a residual cross-modal take-over is maladaptive which is reflected in an inverse relation to the speech recognition ability with a CI (Buckley and Tobey, 2011; Doucet et al., 2006; Sandmann et al., 2012). Several studies with deaf individuals and CI users have shown that the effect of deprivation-induced cross-modal plasticity has mostly been localized to the right hemisphere (Cardin et al., 2013; Doucet et al., 2006; Finney et al., 2001; Rouger et al., 2012; Sandmann et al., 2012), either because the right hemisphere is more susceptible to reorganizational changes compared with the left hemisphere (Lazard et al., 2013) or because the right hemisphere is more involved in the processing of sounds with low complexity (Hine and Debener, 2007). How cortical reorganization affects visual abilities of CI users is not yet thoroughly investigated. The aim of this study was therefore to further investigate cross-modal reorganization in CI users and its consequences, by using ecologically valid visual stimuli.

Human face perception has been studied intensively in the past years. Faces, as compared to inanimate objects, are perceived in a specialized manner (Kanwisher, 2000). Face-selectivity has been verified in neuroimaging studies which have identified the occipital face area (OFA) and the fusiform face area (FFA) as core regions in a neural network of face processing (Haxby et al., 2000; Kanwisher et al., 1997; Kanwisher and Yovel, 2006). Face-selectivity can also be observed in electrophysiological responses, in particular the N170 component (approx. 170 ms after face onset) which typically shows the largest amplitudes over occipito-temporal scalp regions in the right hemisphere (Bentin et al., 1996; Bötzel and Grüsser, 1989; Rossion and Jacques, 2008). The N170 component is larger for faces compared to other objects like houses (Rossion and Jacques, 2008). A well-known effect in the domain of face processing is the face-inversion-effect (Eimer, 2000; Haxby et al., 1999; Kanwisher et al., 1998; Sadeh and Yovel, 2010; Valentine, 1988). Inverted (rotated 180° to upside-down) faces are processed differently than upright faces, as revealed by larger N170 amplitudes and delayed latencies (~8 ms; Eimer, 2000) to inverted faces. By contrast, the inversion effect is much less pronounced for other objects (Rossion et al., 2000). McPartland et al. (2004) observed a trend in their study that a faster neural processing speed (assessed by the N170 latency) reflects a better face recognition ability in healthy participants. Nevertheless, not much is known about the relation between the neurophysiology of visual face processing and behavioral correlates. To the best of our knowledge no studies investigating this relation have been conducted with CI users so far.

There is evidence that deaf individuals have advantages in face processing. This is reflected in a more accurate matching of faces (Arnold and Murray, 1998; De Heering et al., 2012) and may have evolved because the deaf focus more intensively on faces in order to compensate the missing auditory input during face-to-face social communication (Kral et al., 2013; Mitchell et al., 2013; Woodhouse et al., 2009). At present it is not well understood whether this advantage applies also to CI users (Rouger et al., 2012). Previous studies have suggested superior lip reading abilities and different patterns of visual language processing in CI users when compared to normal-hearing controls (Giraud and Truy, 2002; Lee et al., 2007; Rouger et al., 2007, 2012). We therefore hypothesized that CI users show superior abilities in face recognition (assessed by the Cambridge Face Memory Test) and lip reading. It is expected that lip reading skills are increased with a longer duration of deafness due to broader experience in lip reading. On the neurophysiological level, we expected advantages in visual face processing abilities in CI users, as is reflected in enhanced neural activity (larger N170 component) or faster processing speed (shorter N170 latency). Furthermore, by mean of distributed source modeling we determined whether CI users show the predicted activation of the auditory cortex during the processing of visually presented face. We investigated whether this cross-modal reorganization has maladaptive consequences on the individual CI benefit, which should be reflected in lower speech perception.

2. Materials and methods

2.1. Participants

Twenty-one post-lingually deafened individuals implanted with a cochlear implant (13 women, 8 men) participated in the study. The participants showed a variety of hearing-loss etiologies and were all unilaterally implanted at the time of testing (Table 1). Fourteen of the CI users got the implant on the right side and seven on the left side. All CI users had been using their implant for at least 12 months on a regular basis, that is, approximately 16 hours a day. The CI experience varied between 12 and 187 months ($M = 54.8$, $SE = 9.1$ months). The duration of severe hearing loss/deafness was subjectively reported by the participants. We defined the duration of deafness based on the time at which the participants could not benefit from hearing aids anymore which was mirrored in very insufficient speech recognition, until the date of implant surgery. The duration of deafness ranged from three to 240 months ($M = 88.7$, $SE = 19.3$ months). The age at onset of hearing loss varied between a very early onset at birth and an acquired hearing loss during adulthood (range: 0–51 years, mean and standard error: $M = 16.4$, $SE = 3.6$ years). Even if the onset of hearing loss was very early in life for some of the participants, the actual onset of profound deafness was always after speech acquisition, which is also reflected in relatively high speech intelligibility scores. None of the CI users had active sign language skills. Additionally, a normal-hearing (NH) control group, matched with the CI users in gender and age, was tested. The mean age of the CI group was $M = 51.1$, $SE = 3.6$ years (range: 20–74 years) and $M = 50.1$, $SE = 3.6$ of the NH group (range: 21–74 years). For further analyses, the hearing score in noise and in silence was measured from each participant at the date of investigation. A standard pure-tone audiogram with headphones was measured to ensure the normal-hearing status of the control group. The boundary of the age-appropriate hearing level was set to <30 dB HL for the frequencies 500 Hz, 1 kHz, 2 kHz, 3 kHz and 4 kHz. The study was conducted in accordance with the local ethical committee guidelines of the University of Oldenburg and in agreement with the declaration of Helsinki. Every participant gave written informed consent before the onset of the experiment.

2.2. Face vs. house discrimination task

The participants performed a face vs. house discrimination task. Images of faces and houses were shown in randomized order on a computer screen, spanning a visual field of 6° horizontally and vertically (Fig. 1). The face pictures were taken from the Harvard Face Database and pictures of houses were taken from the website http://www.zoomap.co.il/. All pictures were equally scrambled, gray scaled and optimally matched in contrast and luminance. The undegraded stimulus material was successfully used in a previous study investigating N170 face processing (De Vos et al., 2012). The pictures could either be upright or inverted (rotation of 180°) which yielded four different picture categories. Before each trial, a fixation cross of 600 ms was presented.

After a uniform jitter lasting between 0 and 1000 ms, a picture was displayed for 250 ms. Pictures were followed by a grey screen presented for approximately 1700 to 2500 ms, indicating a valid response interval. Trial duration was 3 seconds in total. The whole experiment consisted of three blocks with a total duration of 22 minutes. Twelve different pictures were used in each category. A block consisted of 108 pictures in