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Auditory cross-modal reorganization in cochlear implant users indicates audio-visual integration

Maren Stropahl[a,*], Stefan Debener[a,b]

[a] Neuropsychology Lab, Department of Psychology, European Medical School, Carl von Ossietzky University Oldenburg, Germany
[b] Cluster of Excellence Hearing4all Oldenburg, Germany

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ABSTRACT

There is clear evidence for cross-modal cortical reorganization in the auditory system of post-lingually deafened cochlear implant (CI) users. A recent report suggests that moderate sensori-neural hearing loss is already sufficient to initiate corresponding cortical changes. To what extend these changes are deprivation-induced or related to sensory recovery is still debated. Moreover, the influence of cross-modal reorganization on CI benefit is also still unclear. While reorganization during deafness may impede speech recovery, reorganization also has beneficial influences on face recognition and lip-reading. As CI users were observed to show differences in multisensory integration, the question arises if cross-modal reorganization is related to audio-visual integration skills. The current electroencephalography study investigated cortical reorganization in experienced post-lingually deafened CI users ($n = 18$), untreated mild to moderately hearing impaired individuals ($n = 18$) and normal hearing controls ($n = 17$). Cross-modal activation of the auditory cortex by means of EEG source localization in response to human faces and audio-visual integration, quantified with the McGurk illusion, were measured. CI users revealed stronger cross-modal activations compared to age-matched normal hearing individuals. Furthermore, CI users showed a relationship between cross-modal activation and audio-visual integration strength. This may further support a beneficial relationship between cross-modal activation and daily-life communication skills that may not be fully captured by laboratory-based speech perception tests. Interestingly, hearing impaired individuals showed behavioral and neurophysiological results that were numerically between the other two groups, and they showed a moderate relationship between cross-modal activation and the degree of hearing loss. This further supports the notion that auditory deprivation evokes a reorganization of the auditory system even at early stages of hearing loss.

1. Introduction

Speech in human real-world communication typically is based on the integration of information from multiple sensory modalities (Campbell, 2008; Driver and Noesselt, 2008; Rosenblum, 2008). It is well known that visual information during audio-visual (AV) speech perception can substantially improve speech understanding (Campbell, 2008; Grant and Seitz, 2000; Remez, 2012; Ross et al., 2007; Sumby and Pollack, 1954). For hearing impaired individuals visual speech information may be particularly important, as it facilitates participation in daily-life conversations. Individuals that are severely hearing impaired can nowadays regain parts of their hearing with cochlear implants (CI) (Moore and Shannon, 2009). Within some weeks after implantation, most post-lingually deafened CI users appear to adapt reasonably well to the new electrical input (Lenarz et al., 2012; Pantev et al., 2006; Sandmann et al., 2015; Suarez et al., 1999; Wilson and Dorman, 2008). Furthermore, they seem to integrate AV stimuli efficiently after sensory restoration with a CI (Moody-Antonio et al., 2005; Rouger et al., 2007). Nevertheless, patterns of cortical reorganization that developed during sensory deprivation may influence auditory as well as audio-visual processing after sensory restoration. The aim of the present study was to understand better, how cortical patterns of reorganization in hearing impaired individuals relate to audio-visual speech skills.

There is clear evidence for cross-modal cortical reorganization in the auditory and the visual system in post-lingually deaf CI users (Giraud et al., 2001a, 2001b; Rouger et al., 2012; Sandmann et al., 2012; Stropahl et al., 2015; Chen et al., 2016). Similar patterns may

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Abbreviations: AV, audio-visual; CI, cochlear implant; ICA, independent component analysis; MHL, mild to moderate hearing loss; NH, normal hearing; ROI, region of interest

[*] Corresponding author at: Neuropsychology Lab, Department of Psychology, European Medical School, Carl von Ossietzky University of Oldenburg, Ammerländer Herrstraße 114-118, 26129 Oldenburg, Germany.

E-mail address: maren.stropahl@uni-oldenburg.de (M. Stropahl).

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even exist in individuals with modest levels of hearing loss (Campbell and Sharma, 2014). A seminal study demonstrated a causal relationship between auditory cortex cross-modal activation and supranormal visual performance in deaf cats (Lomber et al., 2010). However, in humans, it is still difficult to disentangle deprivation- versus CI-adaptation-induced patterns of cortical reorganization, which would be ideally addressed with a prospective longitudinal study covering different stages of auditory deprivation. Similarly, the functional purpose of cortical reorganization is less well understood (for a review, see Stropahl et al. (2017)). On the one hand, activation of auditory cortex by visual processing seems to impede speech perception with a CI (Doucet et al., 2006; Lee et al., 2001; Sandmann et al., 2012). Accordingly, this pattern of cross-modal take-over has been termed as maladaptive to CI hearing restoration. On the other hand, by focusing on face processing, we found that auditory cortex activation to visually presented faces is positively related to face recognition and lip-reading performance. This pattern seems to be clearly adaptive for daily-life communication with a CI (Stropahl et al., 2015). Our result fits well to observations showing that cortical reorganization following hearing deprivation is not limited to the auditory cortex. Cortical reorganization in the visual cortex appears to positively influence speech perception recovery after implantation (Giraud et al., 2001a, 2001b; Chen et al., 2016). Moreover, a study observed a reorganization of networks of visual and audiovisual speech to potentially support a more efficient integration of audio-visual speech after sensory recovery (Rouger et al., 2012). It can be concluded that cross-modal compensatory changes during hearing deprivation and maybe during CI restoration as well, take place in both visual and auditory sensory systems. Given that post-lingually deafened CI users show a stronger integration of visual and auditory speech than normal hearing individuals (Barone and Deguine, 2011; Cappe et al., 2009; Desai et al., 2008; Rouger et al., 2007, 2008, 2012; Tremblay et al., 2010), it is tempting to conclude that AV speech processing may be related to cross-modal patterns of auditory cortical reorganization.

In this study, we investigated the possible relationship between auditory cross-modal reorganization and AV integration skills. We used the McGurk illusion to measure audio-visual speech skills (McGurk and Macdonald, 1976). The illusion occurs if the visual speech of a talker speaking a syllable (e.g. ‘Ga’) is simultaneously presented with an incongruent auditory syllable (e.g. ‘Ba’). The person seeing the incongruent AV combination typically perceives neither the visual nor the auditory component of the AV token but a fusion of the two components (e.g. ‘Da’). Those fusion percepts reflect audio-visual integration (MacDonald and McGurk, 1978; McGurk and Macdonald, 1976). To test the hypothesis of a relationship between cross-modal take-over and AV speech skills we conducted an EEG study and compared post-lingually deafened CI users, mild to moderately hearing impaired individuals and normal hearing controls. Using EEG source localization, auditory cross-modal activation to the face-selective N170 component (Bentin et al., 1996; Bötzel and Grüsser, 1989; Rossion and Jacques, 2008) and AV integration based on the McGurk paradigm were measured. We hypothesized a stronger amount of visual take-over, that is, more auditory cortex activation for faces presented in silence, in CI users compared to age-matched normal hearing controls. We also investigated the relationship between the amount of cortical reorganization and the amount of sensory deprivation and included a third group of mild to moderately hearing impaired individuals. We expected to see more cross-modal take-over in the hearing impaired group when compared with normal hearing individuals. Moreover, based on the hypothesis that cross-modal reorganization may be dependent on the level of hearing deprivation as well as on successful hearing restoration, we expected to see less take-over in the hearing impaired group when compared to CI users. Furthermore, we hypothesized that cross-modal activation in CI users is associated with AV integration strength and CI users were expected to have enhanced lip-reading skills compared to both other groups.

2. Materials and methods

2.1. Participants

In total 53 adults participated in the experiment, none of them reported acute neurological or psychiatric conditions and all confirmed normal or corrected-to-normal vision. The study was approved by the local ethical committee of the University of Oldenburg and conducted in agreement with the declaration of Helsinki. Participants gave written informed consent before the experiment.

The sample consisted of a CI group, a group of individuals with mild to moderate hearing loss (MHL), and a normal hearing (NH) control group. The mean age of the 18 CI users was $M = 58.5$ years, $SE = 3.8$ years. All CI users (8 women) were unilaterally implanted (right ear $n = 13$). Participants subjectively reported their duration of deafness as the time that elapsed between speech recognition with hearing aids being insufficient and CI surgery. All CI users became deaf after acquiring aural language skills (post-lingually). The individual duration of deafness ranged from 1.5 months up to 18 years ($M = 61$ months, $SE = 12.5$ months). None of the CI users had active sign language skills. Most of the CI users showed a progressive hearing loss with a broad age range of onset (mean age $M = 24.8$ years, $SE = 5.2$ years), the corresponding demographics are listed in Table 1. The CI users had been using their CI approximately 16 h per day for at least 12 months. The residual hearing was assessed as the hearing threshold on the ear contralateral to the CI and measured before conducting the experiment.

The MHL group consisted of 18 mild to moderately hearing impaired individuals (age: $M = 69.3$ years, $SE = 1.68$ years). None of the MHL individuals used hearing aids and most of them were unconscious of their degree of hearing loss. The mean hearing loss (averaged pure tone hearing loss from 1 kHz to 4 kHz) ranged from 24 dB HL to 60 dB HL with a mean of $M = 42$ dB HL ($SE = 3$). Hearing thresholds of the MHL group are plotted in Fig. 1. The MHL group had a significantly higher mean age compared to the other two groups (MHL vs. CI $t(34) = -2.55$, $p = 0.03$).

As a control group, 17 normal hearing (NH) individuals were tested with a mean age of $M = 57.2$ years, $SE = 4.3$ years. NH controls were gender and age-matched (maximum difference ≤ 5 years) to the CI group, only for the oldest CI participant a match could not be found. The mean age of the CI and the NH groups did not show a significant difference. Hearing thresholds were measured prior to the experiment ensuring that thresholds were below 35 dB HL for the frequencies between 0.5 and 4 kHz, with few exceptions.

2.2. Experimental design

Since the aim of the study was to relate auditory cross-modal reorganization to AV integration skills, a subset of McGurk AV tokens of the freely available OLAVS stimuli was used (Stropahl et al., 2016). In total six AV tokens including six different talkers (three female and three male talkers) and two different AV syllable combinations (audio ‘Ba’/visual ‘Ga’ and audio ‘Pa’/visual ‘Da’) were used (see Table 2). The AV tokens were selected based on their prior probability in normal hearing controls, in order to evoke a fusion percept in about 70% of the presentations (for details see Stropahl et al., 2016). Incongruent AV tokens were presented 20 times each, giving a total number of 120 AV incongruent trials. Furthermore, 240 unimodal and 120 AV congruent trials were presented.

All trials including visual speech began with a 1 s still image of the talker, consisting of the last frame before movement onset. Still image onset was used to analyze cross-modal reorganization to static face stimuli. The still image was followed by the spoken syllable, giving a total duration of approx. 2 s for each clip. A schematic trial set-up is presented in Fig. 2. Participants were seated in a sound-shielded booth, 1.5 m in front of a 24-in. monitor. Video size was set to