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Research paper

Enhanced audio–visual interactions in the auditory cortex of elderly cochlear-implant users

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ABSTRACT

Auditory deprivation and the restoration of hearing via a cochlear implant (CI) can induce functional plasticity in auditory cortical areas. How these plastic changes affect the ability to integrate combined auditory (A) and visual (V) information is not yet well understood. In the present study, we used electroencephalography (EEG) to examine whether age, temporary deafness and altered sensory experience with a CI can affect audio–visual (AV) interactions in post-lingually deafened CI users. Young and elderly CI users and age-matched NH listeners performed a speeded response task on basic auditory, visual and audio–visual stimuli. Regarding the behavioral results, a redundant signals effect, that is, faster response times to cross-modal (AV) than to both of the two modality-specific stimuli (A, V), was revealed for all groups of participants. Moreover, in all four groups, we found evidence for audio–visual integration. Regarding event-related responses (ERPs), we observed a more pronounced visual modulation of the cortical auditory response at N1 latency (approximately 100 ms after stimulus onset) in the elderly CI users when compared with young CI users and elderly NH listeners. Thus, elderly CI users showed enhanced audio–visual binding which may be a consequence of compensatory strategies developed due to temporary deafness and/or degraded sensory input after implantation. These results indicate that the combination of aging, sensory deprivation and CI facilitates the coupling between the auditory and the visual modality. We suggest that this enhancement in multisensory interactions could be used to optimize auditory rehabilitation, especially in elderly CI users, by the application of strong audio-visually based rehabilitation strategies after implant switch-on.

1. Introduction

The integration of information from multiple senses is fundamental with regard to performance and perception in everyday life (Driver and Noesselt, 2008). Real-world situations, such as conversing with others, typically involve the integration of different sensory inputs such as visual face movements and speech.

In comparison to information received via one single modality, cross-modal input has been widely shown to facilitate speed as well as accuracy of processing in normal-hearing (NH) listeners (Mahoney et al., 2011; Molholm et al., 2002). This effect is based on the intersensory redundancy and is often referred to as the redundant signals effect (Giard and Peronnet, 1999; Girard et al., 2011; Mahoney et al., 2011; Miller, 1982). Multisensory interactions can be influenced by mild to moderate and extensive hearing loss (Hauthal et al., 2015; Musacchia et al., 2009; Puschmann et al., 2014). For instance, congenitally deaf individuals and CI users show less pronounced visuo–tactile interactions when compared with NH individuals (Hauthal et al., 2015; Landry et al., 2013).

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Individuals with sensorineural hearing loss can regain hearing ability by means of a cochlear implant (CI). This device transforms the acoustic signal into electrical pulses and directly stimulates the residual fibers of the auditory nerve. However, electric hearing is highly unlike acoustic hearing, and the central auditory system needs to adapt to the CI input after implantation (Giraud et al., 2001b; Pantev et al., 2006; Sandmann et al., 2015). This ability of neural adaptation, also referred to as neural plasticity, has been observed throughout the whole lifespan (Engineer et al., 2004; Jäncke, 2009; Merzenich et al., 2014). Thus, it is reasonable to assume that CI users re-establish the ability to audio–visual interaction after implantation. Nevertheless, CI users may show alterations in multisensory interactions, given that these individuals can develop compensatory skills during the period of auditory deprivation and/or after implantation when confronted with the limited signal from the CI. Indeed, behavioral studies have suggested that the CI users' ability to integrate multisensory information is better for audio–visual speech conditions (Rouger et al., 2007), but is impaired for audio-tactile information when compared with NH listeners (Landry et al., 2013). Overall, the impact of temporary deafness and altered sensory experience on multisensory interaction is not well understood, and the neural correlates underlying the multisensory interplay in CI users remain unknown.

From a traditional view, cross-modal information is processed predominantly in multisensory convergence zones of the brain (for a review, see Driver and Noesselt, 2008). According to this view, single sensory modalities do not interplay, and information of these single sensory modalities join in associated areas located in frontal, temporal or parietal areas. However, there is growing evidence for an alternative view, suggesting that multisensory processing also occurs in sensory-specific regions, in particular the auditory, visual and somatosensory cortex (e.g. Ghazanfar et al., 2005; Kayser et al., 2007; Lakatos et al., 2007). It is currently unclear whether multisensory processing in sensory-specific cortices is comparable between CI users and NH listeners. Knowledge about the multisensory processing in CI users could provide important insights into cortical reorganization and perceptual consequences after sensory deprivation and cochlear implantation.

Multisensory interactions can be affected not only by hearing loss but also by aging (Laurienti et al., 2006; Mahoney et al., 2011). In NH elderly individuals, sensory processes are known to decline, and compensatory strategies may be developed by these individuals to overcome the age-related deficits in unisensory processing (e.g. Habak and Faubert, 2000; Lichtenstein, 1992; Nusbaum, 1999). Accordingly, elderly individuals show enhanced facilitation in reaction times (RTs) for cross-modal compared with modality-specific stimulus conditions when compared with younger counterparts (Laurienti et al., 2006; Peiffer et al., 2007). This indicates that elderly individuals make better use of cross-modal information. However, it is currently unknown whether elderly individuals with a CI show similar enhancement in multisensory integration skills when compared with younger CI users. Knowing these improvements may be of clinical interest, given that supranormal skills in multisensory integration could be used to improve and fasten auditory rehabilitation after implantation (Rouger et al., 2007).

In the present study we used electroencephalography (EEG) to investigate the influence of age, temporary deafness and altered auditory experience on the interactions between the auditory and the visual modality. Young and elderly CI users and NH listeners had to detect basic modality-specific (auditory (A), visual (V)) and cross-modal (audio–visual (AV)) stimuli. We used behavioral measures (RTs and Hits) and source localization of event-related potentials (ERPs) to study alterations of audio–visual interactions in post-lingually deafened CI users. Based on previous studies (e.g. Rouger et al., 2007), we hypothesized an enhanced ability to integrate auditory and visual stimuli in CI users compared with NH listeners. Moreover, we expected a greater benefit from cross-modal input than modality-specific input for elderly individuals when compared with their younger counterparts (Laurienti et al., 2006; Peiffer et al., 2007).

2. Material and methods

2.1. Participants

Forty-eight volunteers participated in the present study. Among these participants, forty-two were consistent right-handers, one a consistent left-hander and five ambidexter (Annett, 1970). Twenty-four of the participants were post-lingually deafened CI users, implanted either unilaterally ($n = 22$; 12 right-implanted, 10 left-implanted) or bilaterally ($n = 2$). Regarding the two bilaterally implanted CI users, the 'better' ear was used as stimulation side (i.e. the ear achieving a higher speech perception score in the Freiburg monosyllabic test, Hahlbrock, 1970). CI users were further subdivided into a group of young and a group of elderly individuals. Details on the implant system and the demographic variables can be found in Table 1. All CI users had been using their CI device continuously for at least 12 months prior to the experiment. Similar to previous studies, we used a pragmatic definition of duration of profound hearing loss, as it is often challenging to determine the precise time point of 'onset of profound deafness' and to estimate the 'duration of deafness', especially in individuals with progressive hearing loss (Sandmann et al., 2015). Specifically, we defined the 'age of onset of profound deafness' as the age at which the degree of hearing loss in the specific ear was diagnosed to be too severe to be successfully treated with a conventional hearing aid. Consequently, 'duration of deafness' was defined as the time window between the 'age at onset of profound deafness' and the time point of implantation of the CI device. Within both age groups there was a substantial age variance across the CI users. Therefore, twenty-four sex- and aged-matched NH listeners served as controls. Similar to the CI users, the NH listeners were subdivided into a group of young and a group of elderly individuals. To avoid a potential confound regarding enhanced visual attention, we verified that none of the participants regularly played action video games (Dye et al., 2009). To verify a normal cognitive status, participants performed the clock completion test (Watson et al., 1993) and several subtests of the CERAD-Plus (Consortium to Establish a Registry for Alzheimer's Disease) test battery (verbal fluency, word list memory, constructional praxis, trail making test; Morris et al., 1989). Three of the CI users and their NH counterparts were excluded due to a low score in cognitive status ($n = 1$) or a large number of misses in the speeded response task (>3.0 SD above mean, $n = 2$). Thus, for the analysis the total number of participants was forty-two, with nine young CI users (CI-young: 3 female, mean age: 26.3, range: 18–37, *SD*: 8.3 years), twelve elderly CI users (CI-elderly: 6 female, mean age: 69.3, range: 62–79, *SD*: 6.2 years), nine young NH listeners (NH-young: 3 female, mean age: 27.3, range: 19–39, SD: 8.1 years), and twelve elderly NH listeners (NH-elderly: 6 female, mean age: 67.2, range: 59–79, SD: 6.1 years). The young NH listeners had normal hearing, given that their hearing loss was less or equal than 20 dB in the tested ear (.25–8 kHz). Similarly, the elderly NH listeners had age-appropriate hearing, as defined by less than 15 dB in the low and median frequency range (.25–2 kHz), and less than 40 dB in the high frequency range (4–8 kHz) in the tested ear. None of the participants had a history of psychiatric illness. All participants had normal or corrected-to-normal vision, as assessed by Snellen chart with letters (mean and standard error of the mean: