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Rapid bilateral improvement in auditory cortex activity in postlingually deafened adults following cochlear implantation

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HIGHLIGHTS

- Postlingually deafened adult cochlear-implant (CI) users showed remarkable changes in auditory cortex response after initial CI processor setup.
- Experience-related changes occurred in the contralateral and ipsilateral auditory cortex to the CI and were most pronounced over the first eight weeks of CI experience.
- Long duration of auditory deprivation was related to limited cortical adaptation after implantation.

ABSTRACT

Objective: Cochlear implants (CIs) can partially restore hearing, but the cortical changes underlying auditory rehabilitation are not well understood.
Methods: This prospective longitudinal study used electroencephalography (EEG) to examine the temporal dynamics of changes in the auditory cortex contralateral and ipsilateral to the CI. Postlingually deafened CI recipients ($N = 11$; mean: 59 years) performed an auditory frequency discrimination task after <1 week, 8 weeks, 15 weeks, and 59 weeks of CI use.
Results: The CI users revealed a remarkable improvement in auditory discrimination ability which was most pronounced over the first eight weeks of CI experience. At the same time, CI users developed N1 auditory event-related potentials (AEP) with significantly enhanced amplitude and decreased latency, both in the auditory cortex contralateral and ipsilateral to the CI. A relationship was found between the duration of deafness and the ipsilateral AEP latency.
Conclusions: Postlingually deafened adult CI users show rapid adaptation of the bilateral auditory cortex. Cortical plasticity is limited after long duration of auditory deprivation.
Significance: The finding of rapid and limited cortical changes in adult CI recipients may be of clinical relevance and can help estimate the role of plasticity for therapeutic gain.

1. Introduction

A fundamental characteristic of the central nervous system is to modify its organization and function as a result of experience (Carcea and Froemke, 2013; Kolb et al., 2003). This ability of neural plasticity allows neural circuits to adequately adapt in response to the changing environment (Pekna et al., 2012). On the functional level, neural plasticity can be defined in terms of alterations in the strength, the spectral and temporal selectivity and the latency of the neural response (Engineer et al., 2004; Jakkamsetti et al., 2012). On the structural level, animal studies have found experience-related changes for instance in cortical thickness, dendritic

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branching, spine density and the number of synapses per neuron (Globus et al., 1973; Katz and Davies, 1984; Sirevaag and Greenough, 1987; Volkmar and Greenough, 1972). Functional and structural changes occur not only during development, but also in the adult brain (Engineer et al., 2004; Jäncke, 2009), although experiences early in life may have quantitatively and qualitatively different effects (Kolb et al., 2003). The intrinsic capacity for brain plasticity throughout the entire lifespan supports recovery in conditions such as stroke, traumatic brain injury and neurodegenerative diseases (Nithianantharajah and Hannan, 2006; Pekna et al., 2012). This view has led to the development of therapeutic interventions that exploit neuroplasticity to achieve strengthening or corrective neurological changes in the brain (Nahum et al., 2013). Hence it is likely that adults with hearing loss benefit from auditory training programs. Indeed, the efficiency of individual computer-based auditory training in these individuals has recently been discussed (Henshaw and Ferguson, 2013).

The rehabilitation of hearing with a cochlear implant (CI) would not be possible without the capacity of the central auditory system to change as a result of experience (Moore and Shannon, 2009). CIs can partly restore hearing in individuals suffering from profound hearing loss. Although electrical hearing with a CI is highly unnatural and impoverished, CI recipients usually adapt to the new, artificial input provided by the CI (Krueger et al., 2008). After implantation, CI users develop enhanced speech recognition ability over the first months after implantation (Lenarz et al., 2012). At the same time, they show changes in the auditory cortex, in particular increased evoked responses (Pantev et al., 2006) as well as altered specificity of secondary auditory and association areas (Giraud et al., 2001). Cortical reorganization following implantation may be based on alteration in Ca^{2+} dependent signaling events (Tan et al., 2008) and seems to be located both in the contralateral and the ipsilateral hemisphere to the CI (Kral et al., 2002; Sandmann et al., 2009). Thus, altered experience trough electrical input after implantation leads to functional changes in the central auditory system (Lazard et al., 2014) and may counteract maladaptive changes caused by sensory deprivation (Sandmann et al., 2012). How the temporal dynamics of experience-related cortical changes in CI users relate to individual differences such as for instance duration of deafness and age at implantation is currently not known.

Previous longitudinal studies on prelingually deaf children confirmed strong changes in auditory evoked brain activity after implantation (Sharma et al., 2005, 2007). These studies have used electroencephalography (EEG) and found that children implanted at early age (<3.5 years) developed a reduction in the latency of auditory event-related potentials (AEPs) and reached latencies comparable to that of normal-hearing peers between 3 and 6 months after initial CI processor setup. The reduction in AEP latency was clearly limited in late-implanted children (>7 years) (Sharma et al., 2005, 2007), confirming the view of a sensitive period for cochlear implantation (Kral and Sharma, 2012). Regarding postlingually deafened adults, the process of cortical changes following implantation is less well explored. Pantev and colleagues (2006) have used magnetoencephalography (MEG) and sophisticated radiofrequency shielding to document the changes specifically in the auditory cortex contralateral to the CI. This was done for two postlingually deafened adult CI users who developed magnetic N1m responses over the first year after initial CI processor setup and achieved similar amplitude compared with normal-hearing listeners. These results support the findings from a previous positron emission tomography (PET) study which showed an increase in activation in the auditory association areas over an average interval of 40.9 months (Naito et al., 2000). It is likely that plastic changes occur most prominently during the first few weeks after implantation (Green et al., 2008). However, for postlingually deafened adult CI recipients, the capacity and time course of plastic changes after implantation in auditory cortex giving rise to hearing with a CI are not well understood.

A better understanding of cortical changes after implantation is of clinical relevance because targeted therapies that can stimulate plasticity may accelerate and enhance aural rehabilitation after implantation. Indeed, for CI users accumulating evidence suggests that targeted auditory training maximizes the benefits of the implant device not only in the poor but also in the good CI performers (Fu and Galvin, 2008). This finding clearly indicates that CI users typically do not exploit all of the (degraded) information available from the CI signal (Moore and Shannon, 2009). To better harvest the role of plasticity for therapeutic gain, the principal aim of the current prospective longitudinal study was to better describe the temporal dynamics of auditory cortex adaptation during rehabilitation with a CI. Here we used EEG which is a non-invasive technique that allows measuring the auditory cortex response *bilaterally* and *repeatedly* in CI users (Debener et al., 2008). In postlingually deafened adult CI users, we studied AEP changes in the contralateral and ipsilateral auditory cortex over the first months after implantation which addresses a research question that has been under-investigated so far. In previous EEG or MEG studies, the description of AEP changes (and of their magnetic counterparts) in adult implantees was restricted to the sensor level (Jordan et al., 1997; Plotz et al., 1996) or to the contralateral auditory cortex (Pantev et al., 2002, 2006). To better understand experience-related changes in the *bilateral* auditory cortex, we tested eleven adult CI recipients with an auditory discrimination task in four sessions over the period of one year after implantation. We used complex frequency-modulated (FM) sweeps, because frequency modulation is a ubiquitous sound feature in human language (Altmann and Gaese, 2014). Our results point to remarkable improvements in auditory discrimination abilities and auditory cortex responses, showing clear signs towards normalization with increasing CI use in postlingually deafened adults.

2. Methods

2.1. Participants

Twenty-four individuals (12 females, 12 males) took part in the present study. Eighteen participants were consistent right-handers, four were consistent left-handers and two were ambidexter (Annett, 1970). Twelve of the participants were postlingually deafened CI users that were implanted unilaterally. One of the (left handed) CI users dropped out for health reasons after the first recording session. Among the remaining eleven CI users, seven individuals were implanted in the right ear and four in the left ear (Table 1). The CI users had either a Cochlear Nucleus CI system with a CI512 processor (seven participants) or a Medel Pulsar or a Medel Concerto system with an Opus 2 processor (four participants). The implantees were measured in four sessions after implantation. On average, the time between the initial CI processor setup and the respective EEG session was 4 days (SEM: 1.6), 56 days (SEM: 9.2), 106 days (SEM: 8.6), and 412 days (SEM: 25). Thus, on average the recording sessions took place 0.5 week, 8 weeks, 15 weeks, and 59 weeks after the initial CI processor setup. In accordance with the clinical practice, all CI users followed a standard aural/oral therapy over approximately three months in parallel with the study. During this time, the CI users attended every two weeks half a day individually adapted auditory training sessions. Often it is difficult to estimate the exact point in time of 'onset of profound deafness', and to derive from that an estimate for the 'duration of deafness', in particular in individuals with progressive hearing loss. We therefore used a pragmatic definition of