

Beta-Band Activity in Auditory Pathways Reflects Speech Localization and Recognition in Bilateral Cochlear Implant Users

Daniel Senkowski,^{1,2,*} Ulrich Pomper,^{1,2} Inga Fitzner,¹ Andreas Karl Engel,¹ and Andrej Kral^{1,3}

¹Department of Neurophysiology and Pathophysiology, University Medical Center Hamburg-Eppendorf, Martinistr. 52, Hamburg, Germany

²Department of Psychiatry and Psychotherapy Charité-Universitätsmedizin, Berlin, St. Hedwig Hospital, Große Hamburger Str. 5–11, Berlin, Germany

³Institute of Audioneurotechnology, Department of Experimental Otolaryngology, ENT Clinics, Hannover School of Medicine, Feodor-Lynen-Str. 35, Hannover, Germany

Abstract: In normal-hearing listeners, localization of auditory speech involves stimulus processing in the postero-dorsal pathway of the auditory system. In quiet environments, bilateral cochlear implant (CI) users show high speech recognition performance, but localization of auditory speech is poor, especially when discriminating stimuli from the same hemifield. Whether this difficulty relates to the inability of the auditory system to translate binaural electrical cues into neural signals, or to a functional reorganization of auditory cortical pathways following long periods of binaural deprivation is unknown. In this electroencephalography study, we examined the processing of auditory syllables in postlingually deaf adults with bilateral CIs and in normal-hearing adults. Participants were instructed to either recognize (“recognition” task) or localize (“localization” task) the syllables. The analysis focused on event-related potentials and oscillatory brain responses. N1 amplitudes in CI users were larger in the localization compared with recognition task, suggesting an enhanced stimulus processing effort in the localization task. Linear beamforming of oscillatory activity in CI users revealed stronger suppression of beta-band activity after 200 ms in the postero-dorsal auditory pathway for the localization compared with the recognition task. In normal-hearing adults, effects for longer latency event-related potentials were found, but no effects were observed for N1 amplitudes or beta-band responses. Our study suggests that difficulties in speech localization in bilateral CI users are not reflected in a functional reorganization of cortical auditory path-

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*Correspondence to: Daniel Senkowski, Ph.D., Department of Psychiatry and Psychotherapy, Charité-Universitätsmedizin Berlin, St. Hedwig Hospital, Große Hamburger Strasse 5–11, Berlin 10115, Germany. E-mail: daniel.senkowski@charite.de

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Key words: deafness; oscillatory activity; EEG; cortical plasticity; beta-band responses

INTRODUCTION

Cochlear implants (CIs) are among the most successful neuroprosthetic devices and remarkable brain plasticity after cochlear implantation has been shown both in humans, using non-invasive electroencephalography [EEG; Doucet et al., 2006, Sandmann et al., 2009], as well as in animals, using invasive recording techniques [Kral and Sharma, 2012]. To utilize the advantages of binaural over monaural hearing, like improved speech perception and better sound localization [Blauert 1996; Hawley et al., 2004], an increasing number of CI candidates nowadays receive bilateral implants. Although bilateral CI users perform well in speech localization tasks when interaural level differences are high, they perform poorly when relying on interaural time differences (ITDs), e.g., when localizing speech from the same hemifield [van Hoesel and Tyler, 2003, Litovsky et al., 2009]. The primary reason for this difficulty may be the artificial electrical stimulation by the CIs, which distorts ITD cues when translated into neural activity [Hancock et al., 2012; Smith and Delgutte 2007]. In this case, despite reduced behavioral performance, cortical auditory stimulus processing would be expected to be largely intact. However, it is also possible that the difficulties in sound localization mainly relate to a degeneration of the auditory nerve and brainstem nuclei, following long periods of binaural deprivation [Tillein et al., 2010; Hancock et al., 2010]. This degeneration would lead to a functional reorganization of cortical processes, especially in the spatial auditory pathway. Similarly, a recent study has shown short-latency responses in the auditory cortex of CI users after visual stimulation [Sandmann et al., 2012], indicative for a deafness-induced cortical reorganization. To date, it is unknown how bilateral CI users process auditory speech with small ITDs at the cortical level.

In normal-hearing subjects, sound localization and sound recognition occurs in parallel through distinct cortical pathways [Ahveninen et al., 2006; Alain et al., 2001; Arnott et al., 2004; Tian et al., 2001]. The sound recognition pathway encompasses an anterior-ventral processing stream [Binder et al., 2000], whereas the sound localization pathway encompasses a postero-dorsal route [Brunetti et al., 2005, 2008]. The two pathways are highly interconnected [Kaas and Hackett 2000; Rauschecker and Scott 2009], allowing for an efficient processing of the different features of auditory stimuli in these pathways. To examine the neural mechanisms underlying sound recognition and

sound localization, one can manipulate the task, i.e., recognize vs. localize stimuli respectively, while keeping the stimulation protocol constant. Using such an approach, human EEG [De Santis et al., 2007; Leavitt et al., 2010] and magnetoencephalography [MEG; Ahveninen et al., 2006; Herrmann et al., 2002] studies examining event-related potentials (ERPs) have shown distinct activation patterns between recognition and localization of auditory stimuli, beginning around 100–200 ms after stimulus presentation. Furthermore, there is a relationship between oscillatory responses, in particular in the beta-band (13–30 Hz) and gamma-band (>30 Hz), and the recognition and localization of auditory stimuli [Kaiser et al., 2002a,b]. The involvement of beta-band activity (BBA), which has often been related to motor processing [Neuper et al., 2006], fits with a recently proposed role of the postero-dorsal auditory pathway in sensorimotor control and integration [Rauschecker, 2011].

In this study, we investigated the spatio-temporal dynamics of auditory speech localization in postlingually deaf adults with bilateral CIs and normal-hearing adults. We performed high-density EEG recordings and applied linear beamforming to source localize oscillatory responses in auditory pathways. In both groups, we found differences in ERPs between the localization and recognition tasks, demonstrating a task dependent processing of auditory stimuli. Moreover, in the localization task, we found stronger suppression of BBA in the postero-dorsal auditory pathway in bilateral CI users, demonstrating, for the first time, intact cortical processing of spatial auditory information with small ITDs in this group.

MATERIALS AND METHODS

Participants

Seventeen right-handed postlingually deaf adults with bilateral CIs and 12 normal-hearing adults participated in the study. Due to extensive eye movement and motor artifacts in the EEG data, two CI users were excluded from further analysis. Three additional CI users were excluded due to poor performance in the localization task (performance < 62.5% in half of the blocks). The remaining 12 CI users (nine female, age 50.75 ± 6.27 years) and normal-hearing adults (nine female, age 45.67 ± 13.95 years) were included in the data analysis. Table 1 provides further details about the CI users. All participants had normal or corrected-to-normal vision and provided written informed

TABLE I. Demographic information of CI users

Gender	Age	CI processor (left)	CI processor (right)	Aetiology	Age at onset of deafness (years)	Duration of deafness (left ear)	CI use (left ear)	Duration of deafness (right ear)	CI use (right ear)
Female	58	Med-EL Tempo	Med-EL Opus 2	Slowly progressing	6	46	6	51	1
Female	47	Med-EL Tempo +	Med-EL Opus	Unkown	29	5	13	14	4
Female	55	Med-EL Symphonix	Med-EL Symphonix	Slowly progressing	35	13	7	18	2
Female	54	Med-EL Combi 40+	Med-EL Opus 2	Traumatic brain injury	47	1	6	4	3
Female	43	Med-EI Opus 2	Med-EL Opus 2	Meningitis	3	33	8	34	7
Male	61	Med-EI Tempo +	Med-EL Opus2	Meningitis	7	40	14	46	8
Male	45	Med-EL Opus 2	Med-EL Tempo +	Brain injury & antibiotics	36	0	9	3	6
Female	46	Med-EL Opus 2	Med-EL Opus 2	Unkown	36	7	3	6	4
Male	43	Med-EL Tempo +/Opus 2	Med-EL Tempo +/Opus 2	Meningitis	5	32	7	28	11
Female	49	Med-EL Tempo+	Med-EL Tempo +	Acute hearing loss	left: 34; right: 36	1	15	0	14
Female	50	Med-EL Pulsar	Med-EL Pulsar	Unkown	3	45	3	44	4
Female	58	Med-EL Opus 2	Med-EL Combi 40	Traumatic brain injury	12	40	6	31	15

consent. The study was conducted in accordance with the Declaration of Helsinki and was approved by the review board of the local ethics commission. Participants were reimbursed for participation.

Procedure and Stimuli

Participants were presented with a continuous stream of auditory syllables (/ga/ or /ta/). Each syllable had a duration of 300 ms and was presented at 65 dB SPL at angles of eccentricity of 10° or 50° from two speakers (Bose Companion® 2) in the right hemispace (Fig. 1A). The reasons why we presented stimuli from the right side were twofold. First, the key goal of our study was to examine the neural signatures of auditory speech localization in bilateral CI users. Thus, by presenting stimuli from the right hemispace, we were able to induce stronger responses in the speech dominant left hemisphere. Second, due to time constraints (the experiment lasted 3–4 hours, including preparation of the EEG cap and practicing of the tasks), we were only able to present stimuli to one hemispace. The speakers were located at the height of the participant’s ears and were hidden behind a sound permeable cloth to avoid visual cues that could improve sound localization performance. A fixed 700 ms interval, after which

pink noise was presented for 100 ms at 65 dB SPL, followed the offset of each syllable. Participants were instructed to press a button with their left or right index finger after the noise sound to indicate either which syllable was presented (i.e. “recognition” task) or from which location the syllable was presented (i.e. “localization” task). An interval between 1,700 and 2,100 ms (mean 1,900 ms) followed the offset of the pink noise before the onset of the next trial (Fig. 1B). The two tasks were conducted block-wise and alternated after every second block. In total, 24 blocks (12 recognition and 12 localization blocks) were presented, each comprising 40 trials. Blocks in which the behavioral performance was significantly below chance level in a binominal test (i.e., below 62.5%) were repeated at the end of the experiment. This criterion led to a presentation of additional 19 localization blocks in six CI users (range of additional blocks: 2–4). Only blocks in which the performance was significantly above chance level were included in the analysis. The syllables were presented equally often from both locations in randomized order. Importantly, the physical stimulation was identical in both tasks. Throughout the experimental blocks, participants were instructed to look at a central fixation cross on a computer screen and were monitored using a surveillance camera. Behavioral performance, defined as the hit rate, was statistically examined in an ANOVA with the

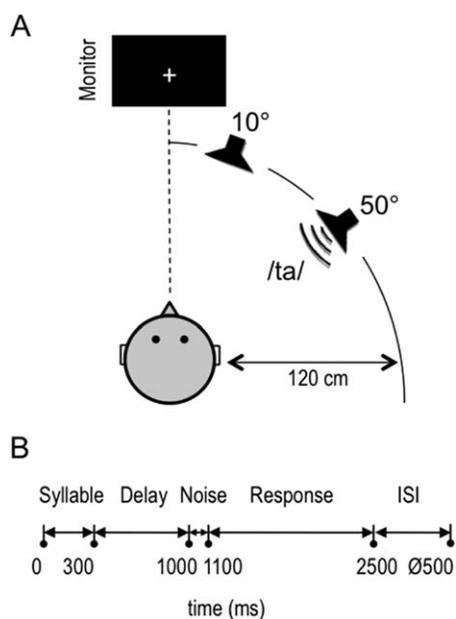


Figure 1.

Experimental setup. **(A)** Illustration of a trial in which the syllable /ta/ was presented at 50° from the right hemifield. Participants were instructed to look at a central fixation cross. Speakers were located at the height of the participant's ears and were hidden behind a sound permeable cloth (not shown on the figure) to avoid visual cues that could improve sound localization performance. **(B)** Timing of a single trial. Syllables with a duration of 300 ms were followed by a 700 ms delay period without stimulation. After the delay period, pink noise was presented for 100 ms, after which participants pressed a button with their left or right index finger to indicate either which syllable was presented (i.e., “recognition” task) or from which location the syllable was presented (i.e., “localization” task).

between-subject factor Group (CI users vs. controls) and the within-subject factor task (recognition vs. localization).

In addition to the blocks in which participants processed stimuli binaurally, the behavioral performance was also monitored under monaural hearing. This was done to explore whether the task performances increased under binaural compared with monaural hearing. Before the main experiment, CI users switched off their right or their left CI device and had a short conversation with the experimenter to familiarize themselves with monaural hearing. In normal-hearing adults, earplugs were plugged into one ear (left or right) to resemble monaural hearing. For each participant (CI users and controls), two blocks per task were conducted under monaural-left and monaural-right hearing conditions. The behavioral performance in the monaural hearing condition was compared with the behavioral performance in the first two blocks of the binaural main experiment using a repeated measures ANOVA with the between-subject factor Group (CI users vs. controls), and the within-subject factors Hearing (mon-

aural vs. binaural) and Task (recognition vs. localization). In addition, potential hearing differences between the left and right ear were examined by an ANOVA with the factors side (left vs. right), task (recognition vs. localization), and group (CI users vs. controls).

EEG Recordings and Data Pre-processing

High-density EEG recordings were acquired from up to 126 scalp electrodes mounted into an elastic cap (Falk Minow Services, Herrsching, Germany) and two additional electrooculogram electrodes to monitor horizontal and vertical eye movements. To protect CI devices, electrodes that were placed above or close to the devices were not filled with electrode gel and therefore not recorded (mean = 11 channels, range = 6–14). For the scalp level analysis of ERPs, only those electrodes that were recorded in all participants (CI users and controls), were used (101 electrodes). This was done because the performed analyses, like running *t*-tests, require the same number of electrodes across participants. For the source reconstruction of oscillatory responses, all electrodes recorded in CI users were included. This was done to increase the accuracy of the beamforming algorithm. In addition, each participant from the control group was matched with one CI user, considering the best match in gender and age. To assure that differences in the number of electrodes between CI users and controls do not account for differences in findings, only those electrodes that were recorded in the CI users were used for the beamforming analysis in the matching controls.

EEG data were recorded with a passband of 0.016–250 Hz and digitized at a sampling rate of 1,000 Hz. An electrode that was placed on the tip of the nose served as reference. Data analysis was performed in Matlab (MathWorks, Natick, MA) and the Matlab-toolboxes EEGLAB [Delorme and Makeig, 2004; <http://www.sccn.ucsd.edu/eeGLab>] and Fieldtrip [Oostenveld et al., 2011; <http://www.ru.nl/fcdonders/fieldtrip>]. Off-line pre-processing of data was done by interpolating channels that contained continuous artifacts throughout the recording (CI users: mean = 3.9 channels, range 0–7; normal-hearing controls: mean = 3.3, range 0–5), re-referencing to common average, 0.3–125 Hz bandpass filtering, and downsampling to 500 Hz. For artifact removal, epochs containing non-stereotyped artifacts (e.g., cable movement, swallowing) were manually removed. Furthermore, extended infomax independent component analysis (ICA) was applied. During the analysis of oscillatory responses, we observed that the removal of CI artifacts was more effective when ICA was conducted on epoched data and applied separately on low-pass and high-pass filtered data. Therefore, each dataset was split into a 35 Hz low-pass and a 25 Hz high-pass filtered dataset and epoched between –500 to 800 ms. Then, ICA was performed separately for low- and high-pass filtered data. The separate ICA-based removal of

artifacts in low- and high-pass filtered data has been recently shown to be efficient in healthy participants [Hipp et al., 2011]. While oscillatory responses were analyzed separately for low- and high-pass filtered data, only 35 Hz low-pass filtered data were used for the analysis of ERPs. Independent components representing artifacts such as eye blinks, horizontal eye movements, electrocardiographic activity, or artifacts by the implants, were removed from the EEG data by back-projecting all but these components. Previous studies have shown that ICA can be effectively used to remove CI artifacts [Debener et al., 2008; Sandmann et al., 2009; Viola et al., 2009, 2011]. Finally, all trials that still exceeded a threshold of 100 μV were rejected automatically. Error trials were excluded from the analysis.

Analysis of Event-Related Potentials

A baseline from -150 to -50 ms before the onset of auditory syllables was subtracted from each epoch. The analysis of ERPs consisted of three levels. In the first level of analysis, time windows with the largest difference between recognition and localization tasks were determined by calculating point-wise running t -tests between the two tasks. To account for alpha error accumulation due to multiple testing, a significant difference between the two tasks was defined as at least 20 ms of continuous data (i.e., 10 consecutive sample points) meeting an alpha criterion of 0.05 [Guthrie and Buchwald, 1991]. Based on this procedure, a short-latency (100–150 ms), mid-latency (250–300 ms), and long-latency time-window (450–600 ms) were selected for the analysis. In line with the literature [Friedrich et al., 2006; Sanders and Neville 2003; Schepers et al., 2013], and in agreement with the topography of the ERPs, different regions of interest (ROIs) were selected for the three time windows: a fronto-central (13 electrodes, short-latency window), an occipital (17 electrodes, mid-latency window), and a medio-central (20 electrodes, long-latency window) ROI. In the second level of analysis, two-way repeated measures ANOVAs were computed for the selected time intervals and ROIs that included the within-subjects factor Task (recognition vs. localization) and the between-subject factor Group (CI users vs. controls). Significant interactions were followed up by separate ANOVAs and linear mixed model (LMM) analyses for CI users and control participants. The LMM analysis was conducted to investigate whether findings in the follow-up ANOVAs relate to differences in difficulty between the two tasks. The LMM analyses included the within-subject factor Task (recognition vs. localization) and the covariate Hit rate (hit rates in the recognition and localization tasks).

Analysis of Oscillatory Responses

Time-frequency (TF) transformations were computed using fast Fourier transforms (FFTs) on Hanning-tapered

time-windows for low frequency activities (i.e., 2–30 Hz). For the TF transformation of high frequency activities (i.e., 30–120 Hz) the multitaper method was used [Mittra and Pesaran, 1999]. For the analysis of low frequency and high frequency activities, fixed time windows ($\Delta T = 267$ ms and $\Delta T = 150$ ms) and fixed spectral smoothing ($\Delta f = \pm 5$ Hz and $\Delta f = \pm 10$ Hz, respectively) were applied on single-trial data. To reveal amplitude normalized signal changes of total power in the poststimulus interval, the average power in the baseline interval (-300 to -100 ms before stimulus onset) was first subtracted and the resulting difference was divided by the baseline interval activity for each frequency as follows: $\text{Pow}(t,f)_{\text{normalized}} = 100 \times (\text{Pow}(t,f)_{\text{poststimulus}} - \text{Pow}(f)_{\text{baseline}}) / \text{Pow}(f)_{\text{baseline}}$.

The statistical analysis of BBA in source space focused on oscillatory responses from 13 to 22 Hz, for a 343 ms time interval (i.e., six cycles at 17.5 Hz), ranging from 28 to 371 ms after stimulus onset. The statistical analysis of source gamma-band activity (GBA) was performed for data from 70–90 Hz, for a 375 ms time window (i.e., 30 cycles at 80 Hz), ranging from 12 to 387 ms after stimulus onset. These TF windows were selected for three reasons. First, BBA and GBA response patterns to auditory stimuli have been previously reported at this latency [Gurtubay et al., 2004; Kaiser et al., 2002a]. Second, during the data analysis we observed that the CI offset artifact in some participants substantially contaminated longer latency activities (>400 ms). Since the removal of ICA components focused primarily on CI onset artifacts, we cannot assure that longer latency offset artifacts were completely eliminated. Finally, the time windows centered at 200 ms fit with the onset of BBA suppression in this study. Due to temporal smearing during the TF transformation, BBA is observed at much shorter latency, especially in CI users (see Results section). Note that the GBA in this study was relatively low in amplitude.

For the analysis of oscillatory responses in source space, a linear beamforming approach was used [Gross et al., 2001; Van Veen et al., 1997]. This method applies an adaptive spatial filter that passes activity from one specific location of interest with unit gain, while suppressing activity from other locations. Since linear beamforming is based on the calculation of the cross-spectral density (CSD) matrix over trials, this approach is particularly suitable for the analysis of total power in the human EEG [Schneider et al., 2008, 2011] and MEG [Senkowski et al., 2011; Siegel et al., 2008]. For the source reconstructions, an anatomically realistic three-shell volume conduction model from a Montreal Neurological Institute (MNI; <http://www.mni.mcgill.ca>) brain template was used. The leadfield matrix was calculated using the boundary element method for each grid point in the brain on a regular 7-mm grid. MNI coordinates were then converted to Talairach coordinates using an algorithm by Lancaster et al. (2007). The source activity at each grid point was estimated by constructing a spatial filter using the leadfield at this point and the CSD matrix. To maximize the sensitivity of the

beamformer to focal sources, we did not apply regularization [Capilla et al., 2013]. For each participant and task, the CSD matrix was calculated between the scalp EEG channels, and separately for a baseline window (centered at -200 ms) and a poststimulus window (centered at 200 ms). Frequencies of 13–22 Hz (centered at 17.5 Hz) and 70–90 Hz (centered at 80 Hz) were used for the beamforming analysis of BBA and GBA, respectively.

Spatial filters for the beamforming analysis were computed separately for CI users and normal-hearing adults based on pooled trials across recognition and localization tasks. The use of a common filter for the recognition and localization tasks ensures that differences in source space activity can be ascribed to power differences in the different tasks and not to differences between filters. Single trials were then projected through the common filter and averaged in source space separately for each task. The statistical analysis of oscillatory responses consisted of two levels. In the first level of the analysis, which served to define ROIs in source space, cluster-based permutation tests [Maris and Oostenveld, 2007] that contrast the recognition and the localization tasks were conducted for the selected TF windows, for the two groups separately. For those regions (i.e., connected significant nodes) that showed significant differences in either group and/or TF window, two-way repeated measures ANOVAs were performed in the second level of analysis. Specifically, the mean power over all voxels within a cluster ROI served as dependent variable, the factor Group (CI users vs. controls) as between-subject factor, and the factor Task (recognition vs. localization) as within-subjects variable. Significant interactions between Group \times Task were followed up by ANOVAs and LMM analyses for CI users and control participants. The LMM analysis included the within-subject factor Task (recognition vs. localization) and the covariate Hit rates (hit rates in the recognition and localization tasks).

RESULTS

Behavioral Data

The ANOVA for the hit rate in the binaural hearing condition using the factors Group (CI users vs. controls) and Task (recognition vs. localization) revealed a significant main effect of Group ($F_{1,22} = 47.06$, $P < 0.001$) and Task ($F_{1,22} = 51.77$, $P < 0.001$), as well as a significant interaction between these factors ($F_{1,22} = 42.03$, $P < 0.001$). The hit rate was higher for controls (98.4%) compared with CI users (87.4%) and higher in the recognition (98.8%) compared with the localization (87.0%) task. Due to the significant Group \times Task interaction, follow-up ANOVAs were conducted separately for the two groups using the factor Task. A significant effect was found for CI users ($F_{1,11} = 54.56$, $P < 0.001$), indicating a significant better performance in the recognition (98.6%) than in the localization task (76.1%). This finding replicates previous reports

showing that bilateral CI users have difficulties with the spatial discrimination of stimuli from the same hemifield. No significant effect was found for the control group ($F_{1,11} = 0.89$, $P < 0.366$).

Next, it was explored whether the behavioral performance differed between monaural and binaural hearing conditions. The ANOVA with the between-subject factor Group, and the within-subject factors Hearing (monaural vs. binaural) and Task revealed significant main effects of Group ($F_{1,22} = 106.11$, $P < 0.001$), Task ($F_{1,22} = 43.13$, $P < 0.001$), and Hearing ($F_{1,22} = 24.41$, $P < 0.001$). The hit rate was higher for controls (98.2%) compared with CI users (81.8%), higher in the recognition (96.8%) compared with the localization (83.1%) task, and higher in the binaural (92.9%) compared with the monaural (87.1%) condition. In addition, significant interactions were found between the factors Group and Task ($F_{1,22} = 48.57$, $P < 0.001$) and between the factors Group and Hearing ($F_{1,22} = 14.80$, $P < 0.001$). Follow-up ANOVAs were calculated separately for the two groups using Task and Hearing as factors. For CI users, this ANOVA revealed a significant main effect of Task ($F_{1,11} = 48.99$, $P < 0.001$) as well as a significant main effect of Hearing ($F_{1,11} = 24.60$, $P < 0.001$). Hit rates were higher for the recognition (98.5%) compared with the localization (75.2%) task, and higher for the binaural (86.9%) compared with the monaural (76.7%) condition. No significant effects were found for the normal-hearing controls (P -values > 0.26). Taken together, these results demonstrate that processing of inputs through the second CI significantly contributes to the localization performance and shows, as expected, that normal-hearing participants can localize sound better than CI users, monaurally as well as binaurally. To test for potential hearing differences between the left and right ear, an additional ANOVA with the factors Side (left vs. right monaural), Task (recognition vs. localization) and Group (CI users vs. controls) was conducted with the hit rate as dependent measure. The ANOVA did not reveal any significant main effects or interactions including the factor Side, indicating no performance differences between monaural left vs. monaural right hearing.

To further examine the possible influence of experience with the implant on behavioral performance in CI users, two-sided Pearson correlation coefficients for time that had passed since implantation of the second device and behavioral performance (i.e., hit rates in recognition minus localization tasks), and for time that had passed between implantation of the first and second device, and behavioral performance, were computed. Both analyses did not reveal significant results (P -values > 0.35). Thus, the duration of experience with the second CI did not affect the results significantly.

Event-Related Potentials

The ERP traces show a typical N1/P2 complex, starting around 100 ms, with larger amplitudes for the control

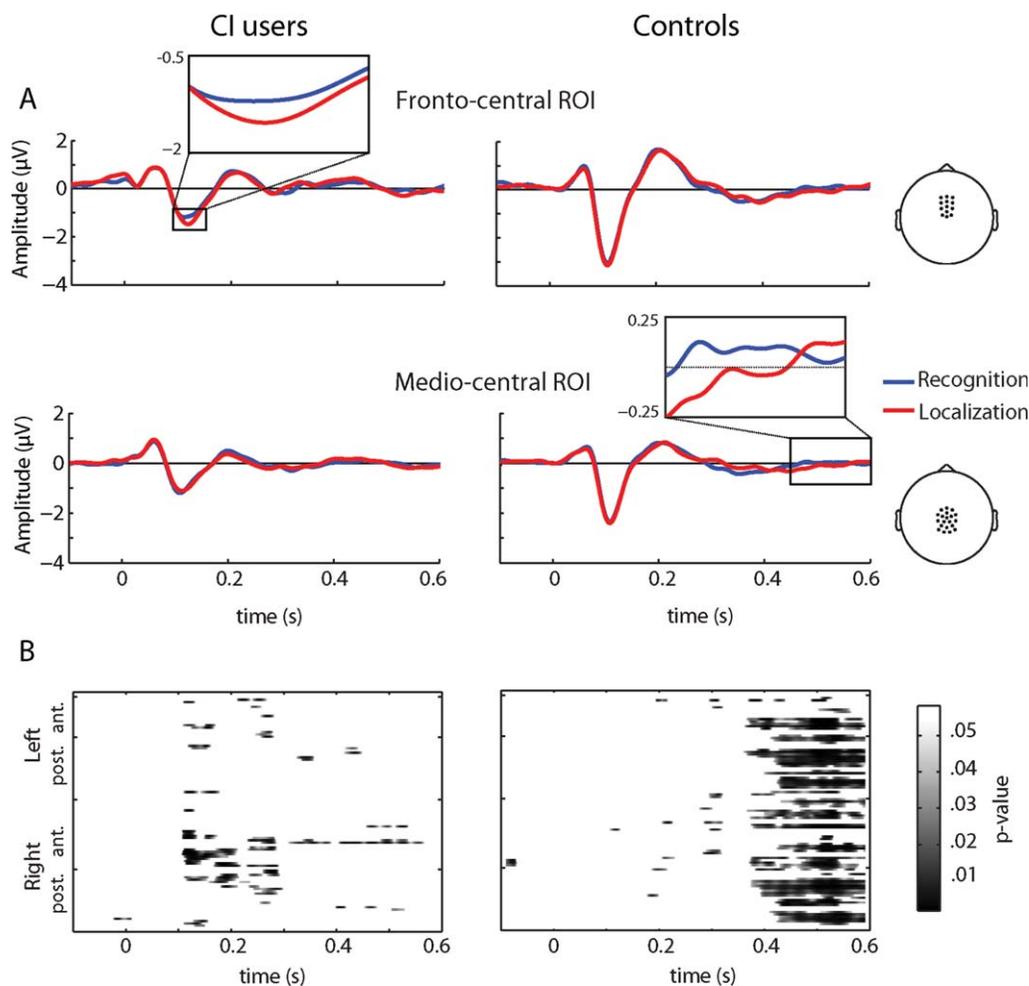


Figure 2.

ERP traces and running *t*-tests between the speech localization and recognition task. **(A)** Grand average ERP traces across a fronto-central (upper panel) and a medio-central (lower panel) region of interest for the localization (blue trace) and the recognition (red trace) tasks of CI users and control participants. The ROIs are illus-

trated in the topography plots on the right. **(B)** Point-wise running *t*-tests between conditions for CI users (left panel) and control participants (right panel) for all electrodes [sorted from anterior to posterior for left (upper part) and right side and midline electrodes (lower part)]. Ant. = Anterior, Post. = Posterior

group compared with CI users (Fig. 2A). Point-wise running *t*-tests (corrected for multiple comparison, as described above) indicate three time windows in which differences between the two tasks may be obtained (Fig. 2B). There were ERP differences between tasks at short-latency (100–150 ms) and at mid-latency (250–300 ms) for CI users (Fig. 2B). For the control group, differences between conditions were most prominent at longer latency (450–600 ms). As described above, a fronto-central, an occipital and a medio-central ROI were selected for the short-, mid-, and long-latency time-windows, respectively.

The ANOVA for the short-latency window, using the factors Group (CI users vs. controls) and Task (recognition vs. localization), revealed a significant main effect of Task

($F_{1,22} = 12.97, P < 0.002$), due to larger negative amplitudes in the localization compared with the recognition task (Fig. 3). Moreover, a significant interaction between Group \times Task was found ($F_{1,22} = 4.47, P < 0.046$). The follow-up ANOVA for CI users revealed a significant main effect of condition ($F_{1,11} = 14.29, P < 0.003$), due to more negative N1 amplitudes in the localization compared with the recognition task. However, the LMM analysis for CI users with the within-subject factor Task and the covariate Hit rate, which was conducted since there were differences in difficulty between the two tasks, did not reveal a significant effect ($F_{1,10.6} = 3.61, P < 0.85$). This shows that differences in task difficulty substantially contribute to the N1 amplitude effect observed in the ANOVA. The follow-

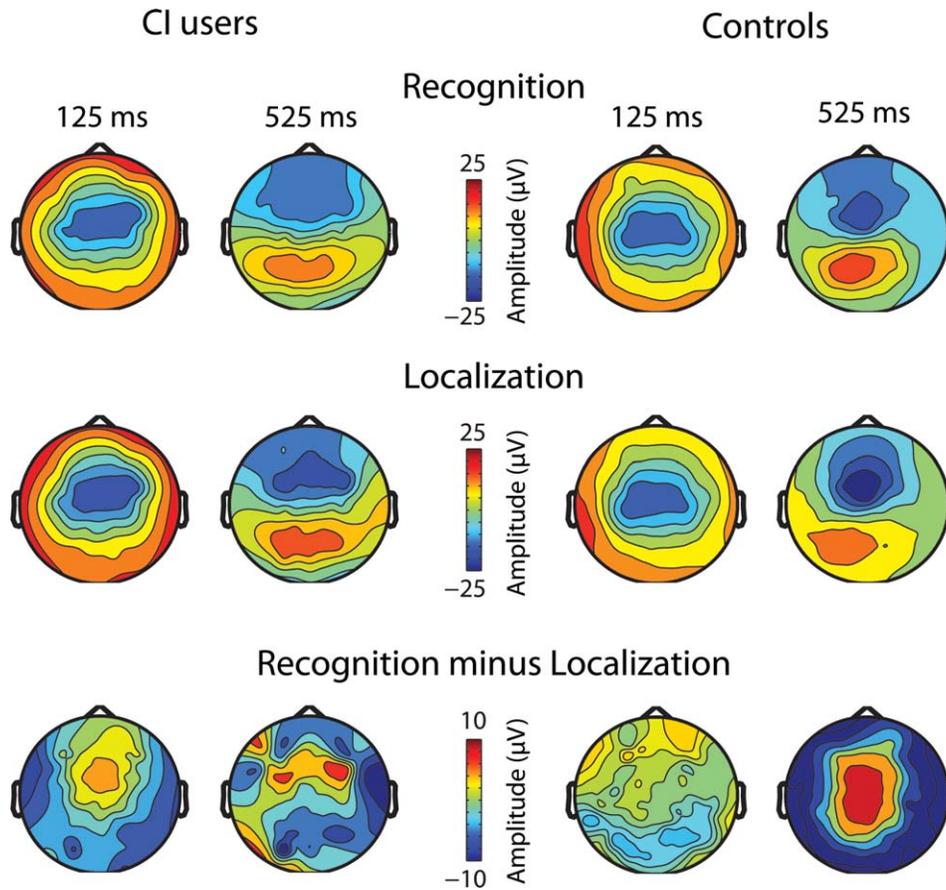


Figure 3.

Topographical maps of ERPs at 125 ms and 525 ms after syllable onset. For CI users, more negative medio-central amplitudes are visible at 125 ms (left panel). For control participants (right panel), differences between conditions were most prominent at a longer latency around 525 ms.

up ANOVA and the LMM analysis for the control group did not reveal significant effects (P -values > 0.25). Moreover, the ANOVA for the mid-latency window did not show any significant effects (P -values > 0.15). The ANOVA for the long-latency window, however, revealed a significant main effect of Task ($F_{1,22} = 4.77$, $P < 0.04$), due to a larger negative deflection in the localization compared with the recognition task. In addition, a significant interaction between Group and Task was found ($F_{1,22} = 11.52$, $P < 0.003$). The follow-up ANOVA for CI users did not reveal any significant differences in long-latency amplitudes between the two tasks ($F_{1,11} = 1.22$, $P < 0.293$). For the control group, a significant main effect of Task was observed ($F_{1,11} = 11.12$, $P < 0.007$), due to more negative amplitudes in the localization compared with the recognition task (Fig. 3). Similarly, a significant difference between tasks was found in the LMM analysis ($F_{1,10} = 9.94$, $P < 0.01$), suggesting that differences in task difficulty did not account for the longer latency ERP effect in the control group.

Oscillatory Responses

The TF representations show a suppression of BBA after stimulus onset in both groups and tasks, whereas no substantial increase in power was found in GBA (Fig. 4). To explore whether the lack of GBA relates to the fact that separate ICA artifact removal procedures were computed for low and high-frequency activity, we computed additional TF representations for non-ICA corrected high-frequency data. In this additional analysis, however, we also did not find robust modulations of GBA. Figure 4 suggests a stronger suppression of lower frequency BBA (around 17 Hz) in the localization compared with the recognition task and indicates slightly larger higher frequency GBA (around 80 Hz) responses in the recognition compared with the localization task, in particular for CI users. At 200 ms, the suppression of BBA showed a widespread topography, whereas only a weak GBA was found (Fig. 5). Next, the cortical sources underlying BBA suppression and GBA were examined.

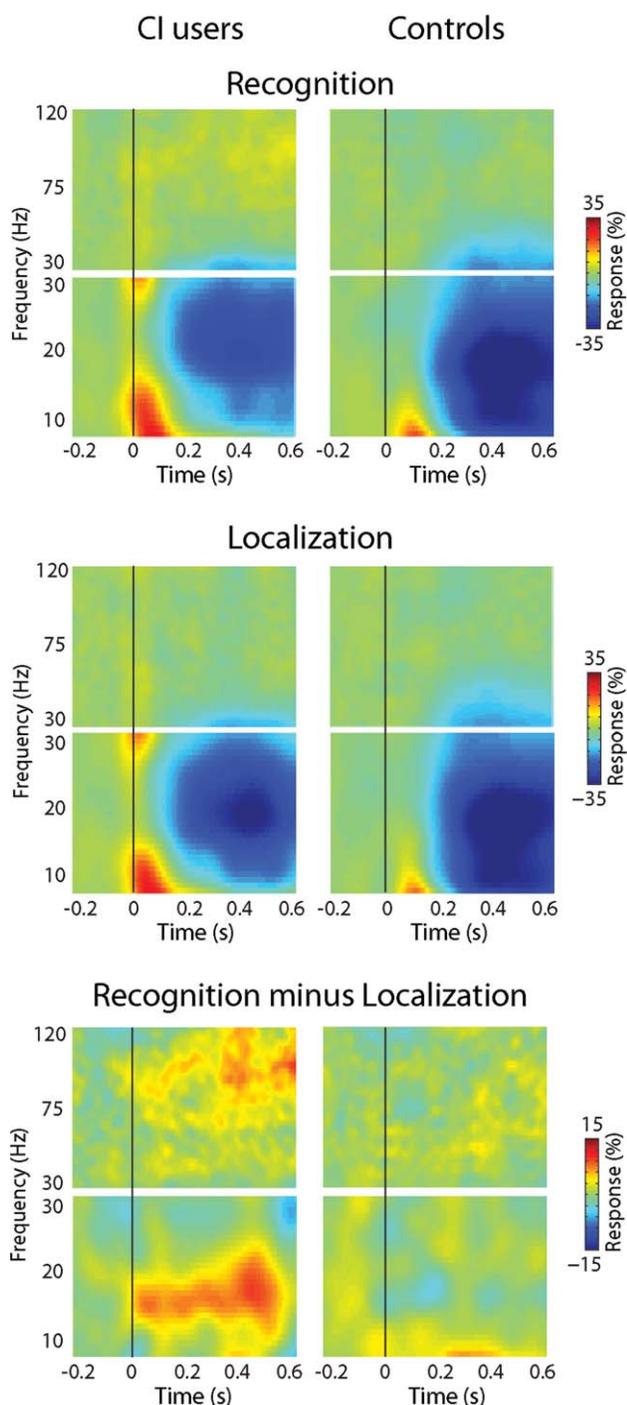


Figure 4.

TF representations of total oscillatory responses (8–120 Hz) at left posterior scalp (mean of 17 electrodes). A strong suppression of BBA is visible in both groups and tasks. The difference TF representations (bottom panels) show a longer lasting difference between the two tasks in the beta-band in CI users.

Linear beamforming of BBA (centered at 200 ms and 17.5 Hz) showed a suppression of BBA in bilateral sensorimotor cortex. Particularly in the localization task for CI users, an additional suppression of BBA was found in left temporo-parietal areas, encompassing the postero-dorsal auditory processing stream (Fig. 6). The cluster-based permutation test revealed significant differences between the two conditions in left parietal and left temporal and superior temporal areas, with the strongest differences in Brodmann area 40 (Talairach coordinates: $-41 -41 58$). The mean ROI activity of BBA (comprising 116 connected voxels in the left hemisphere that showed a significant effect in the cluster-based permutation test) was examined in a repeated measure ANOVA with the factors Group and Task. The ANOVA revealed a significant main effect of Task ($F_{1,22} = 8.03$, $P < 0.010$), indicating a stronger suppression of BBA in the localization compared with the recognition task. Interestingly, the ANOVA also revealed a significant interaction between Group \times Task ($F_{1,22} = 8.33$, $P < 0.009$). Follow-up ANOVAs, which were conducted separately for CI users and controls, revealed a significant main effect of Task particularly in CI users ($F_{1,11} = 33.59$, $P < 0.001$), indicating a stronger BBA suppression in the localization compared with the recognition task. No effect was observed in the normal-hearing group ($P > 0.98$). To control whether differences in task difficulty account for the effect in CI users, an LMM was computed including the covariate Hitrate. The LMM for CI users revealed a significant main effect of Task ($F_{1,12} = 6.60$, $P < 0.026$), due to a stronger BBA suppression in the localization compared with the recognition task. Thus, differences in task difficulty likely do not account for the BBA suppression effect in CI users. To further examine the possible influence of task difficulty on the present findings, we compared the source-localized BBA between CI users with the best ($N = 6$, average hit rate in the localization task = 83.2%) and the worst ($N = 6$, average hit rate in the localization task = 69.1%) performances in the localization task. We used a nonparametric cluster-based permutation test for this comparison. The test did not reveal significant differences between the two groups, further supporting the notion that task difficulty did not substantially contribute to the finding of stronger BBA suppression in the localization compared with the recognition task in CI users. Finally, the cluster-based permutation test for source-localized GBA (centered at 200 ms and 80 Hz) did not reveal any significant cluster (all P -values > 0.187) (Supporting Information Fig. 1).

DISCUSSION

In this study we investigated the neural mechanisms underlying the localization of auditory syllables in postlingually deaf adults with bilateral CIs. CI users benefited from the second implant, particularly in the localization task. The main findings in EEG data for CI users when using both implants were a stronger suppression of BBA in the postero-dorsal auditory pathway and enhanced

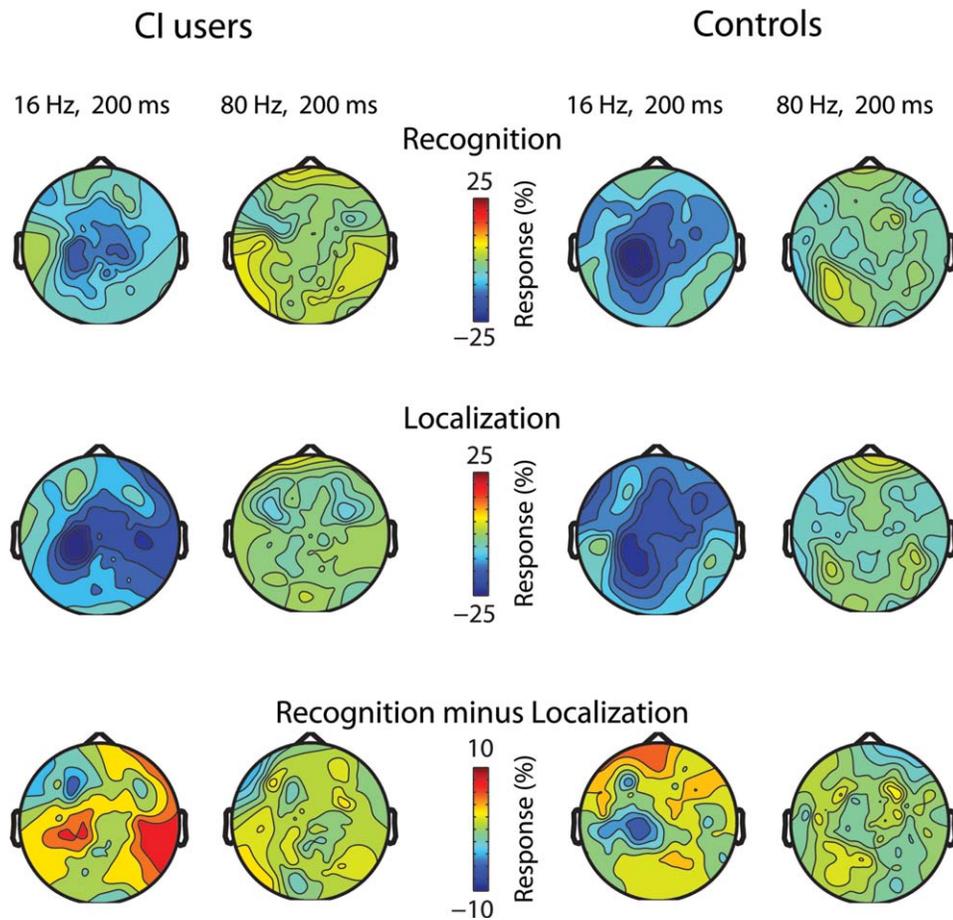


Figure 5.

Topographical maps of total BBA and GBA centered at 200 ms. The figure shows a robust suppression of BBA for both conditions and tasks, whereas there was no obvious power modulation in GBA.

event-related N1 amplitudes in the localization compared with the recognition task. In normal-hearing controls differences between the two tasks were found particularly in longer latency ERPs.

Behavioral Data

The improved performance with two implants in the localization task is in agreement with previous studies that have explicitly addressed this issue [Nopp et al., 2004; van Hoesel and Tyler, 2003]. However, one study, in which noise bursts were presented from various different locations, found that only about half of CI users have a bilateral benefit on location identification within hemifields [Litovsky et al., 2009]. Litovsky et al. (2009) tested CI users 3 months after implantation of the second device. Other studies including CI users who had their second device for longer periods revealed more consistent bilateral benefits in spatial localization tasks [Nopp et al., 2004; van

Hoesel and Tyler, 2003]. This suggests that the auditory localization performance in binaural CI users improves during a time period extending beyond the first 3 months after implantation. In our study, almost all CI users had their second device for more than a year (average 5.3 years) but the duration of the use of the second device was not significantly correlated with the localization performance. This suggests that performance in the present localization task did saturate in most investigated subjects. The absence of a bilateral benefit in the sound recognition task probably relates to the ceiling performance in both the monaural and binaural hearing conditions in this task. In contrast to CI users, there were no performance differences between the two tasks in the normal-hearing control group in the monaural hearing condition. A caveat of the monaural hearing condition was that the earplugs did possibly not eliminate all binaural cues. However, the observation of nearly perfect discrimination performance of stimuli that differed in their angles of eccentricity by 40° fits well with previous studies examining monaural

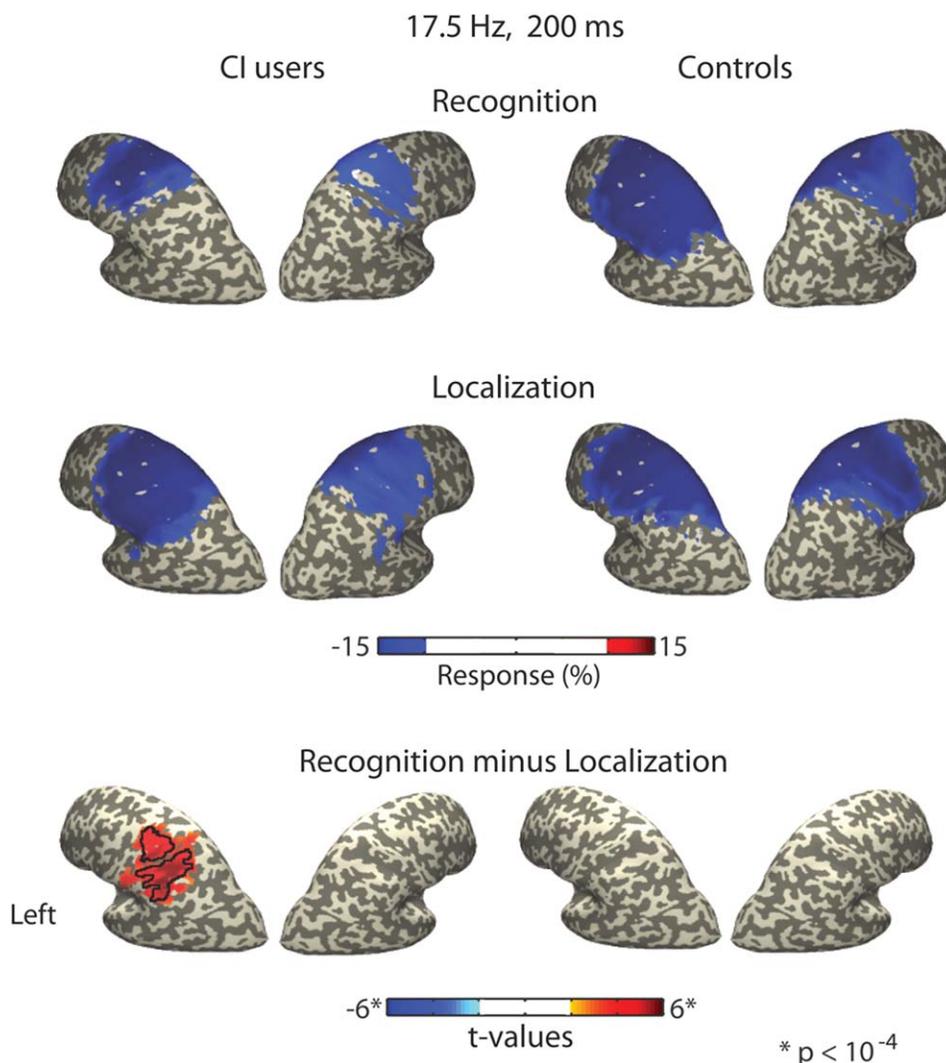


Figure 6.

Linear beamforming of total BBA centered at 17.5 Hz and 200 ms. Across tasks and groups the most robust BBA suppression pattern was observed in bilateral sensorimotor cortex. For CI users, a suppression of BBA was found in left temporo-parietal areas that was stronger in the “localization” compared with the

“recognition” task. Lower panel: Significant voxels, as revealed by *t*-tests, are depicted in red. The bold black line outlines the significant cluster, as revealed by a cluster-based permutation test.

localization performance in normal-hearing adults [Fisher and Freedman 1968; Harris and Sergeant 1971]. Thus, it is likely that the control group would have performed at ceiling level, even if the binaural cues had been completely eliminated.

Although the experimental tasks of our study were basic forced-choice discrimination tasks—discriminate two syllables or two locations—the behavioral performance in CI users was lower in the localization than in the recognition task. This observation fits with previous studies showing that bilateral CI users have difficulties in localizing speech signals, especially when they are presented from the same

hemifield [Litovsky et al., 2009; van Hoesel and Tyler, 2003]. Since ITD processing is an important mechanism for speech localization in one hemifield, in particular when stimuli contain high frequency information above a few hundred Hz, the reduced performance in the localization task in our study likely relates to a reduced ITD sensitivity in bilateral CI users [van Hoesel and Tyler, 2003].

Event-Related Potentials

Bilateral CI users showed larger N1 amplitudes in the localization compared with the recognition task. Similar

differences in ERPs between the localization and recognition of auditory stimuli in normal-hearing adults have been previously reported in the time window of the N1 component and these effects were source localized to putative dorsal and ventral auditory pathways [Ahveninen et al., 2006; Herrmann et al., 2002; Leavitt et al., 2010]. A critical finding in our study in CI users was the higher difficulty in the localization task. The observed effect on N1 amplitudes in CI users should be therefore interpreted in relation to the different degrees of effort that participants have probably invested in processing of the two tasks. Some studies reported an enhancement of N1 amplitudes with increasing task difficulty [Mulert et al., 2007; Rao et al., 2010]. Notably, when the task performance was entered as a covariate into the analysis of the N1 amplitudes in CI users in our study, the significance disappeared. This confirms that differences in task difficulty contributed to the N1 amplitude effect in CI users.

We did not find effects on N1 amplitudes between tasks in normal-hearing adults. For them, both tasks were easy and they achieved nearly perfect performances in the monaural condition already, possibly decreasing the sensitivity of the N1 measurement in this task. This interpretation fits with previous studies lacking in N1 amplitude effects in normal-hearing participants [Alain et al., 2001, 2009]. In our study, significant ERP differences between the localization and recognition of auditory speech in normal-hearing adults were found in particular at longer latency (>400 ms). The widespread topography of this effect, with a medio-central maximum, indicates an involvement of multiple cortical areas. Longer latency differences between the localization and recognition of auditory stimuli have been previously related to activity in inferior fronto-temporal and centro-parietal regions [Alain et al., 2001], which may also be involved in our study. Taken together, we found that attention to object location and object recognition modulates ERPs to auditory syllables in both normal-hearing adults and bilateral CI users. The effects on N1 amplitudes in CI users probably reflect an enhanced effort in stimulus processing in the localization compared with the recognition task, whereas the longer latency effects in normal-hearing adults likely reflect distinct longer latency stimulus processing in auditory pathways.

Oscillatory Responses

Centered around 200 ms after stimulus onset, CI users showed a stronger BBA suppression in the localization task compared with the recognition task. This effect was localized to the postero-dorsal auditory pathway, encompassing parietal, temporal, and superior temporal areas, which have been previously related to spatial auditory processing [Arnott et al., 2004]. Our observation of effects specifically in the left hemisphere possibly relates to the left hemispheric dominance for speech processing and to the fact that stimuli were presented in the right hemifield. Thus, our study demonstrates that spatial discrimination

processing of auditory syllables in CI users includes similar structures to those previously found in normal-hearing persons. This suggests that the artificial signals provided by the implants include sufficient information to be processed in the postero-dorsal auditory pathway. Therefore, the development of signal processing strategies for preserving unambiguous binaural cues, which may include binaurally coherent jitter [Hancock et al., 2012; Laback and Majdak, 2008; but see van Hoesel, 2008], could improve auditory localization abilities of bilateral CI users. The absence of effects in normal-hearing adults may be due to a lack of statistical power. Both tasks were easy for this group, even under monaural hearing conditions. Therefore, it is possible that the effect size in normal-hearing adults may have been too small to be detected in the current sample.

In our study, all bilateral CI users were postlingually deaf. Therefore, although deafness started early in life in some participants, it can be assumed that auditory pathways developed relatively normally. Note that this is in sharp contrast to persons with congenital deafness, which, if not treated during critical development periods, can lead to irreversible impairments in auditory pathways [for a recent review, see Kral and Sharma, 2012; Kral et al., 2009]. Similarly, extended periods of binaural deprivation, as often experienced by CI users, could lead to a degeneration of the auditory nerve and brainstem nuclei. If this would be the case, the time delay between implantation of the first and second device should have had a negative influence on task performance. However, we did not find such a relationship in our analyses. Thus, our study suggests that irreversible consequences of deafness in auditory pathways is probably not the main cause why postlingually implanted CI users have difficulties in spatial discrimination of auditory stimuli, especially those with small ITDs [Tillein et al. 2010; Hancock et al. 2010].

It is of particular interest that the effects in oscillatory responses were found in the beta-band. Stimulus related modulation of BBA has been frequently linked to the preparation and execution of motor processes [Neuper et al., 2006; Pfurtscheller and Lopes da Silva, 1999]. Moreover, BBA has a possible role for behaviorally relevant higher cortical processes [Engel and Fries, 2010], like multisensory integration [Hipp et al., 2011; Senkowski et al., 2006] and decision making [Donner et al., 2009]. Kaiser et al., (2002a) presented lateralized natural (i.e., barking dog sounds) and artificial (i.e., distorted noise) auditory stimuli in a magnetoencephalography study. The authors reported an enhanced BBA suppression over contralateral sensorimotor areas for natural but not for artificial stimuli and suggested that this suppression reflects an automatic preparation for orientation triggered by the natural stimuli. Similarly, the BBA suppression in our study may relate to an enhanced spatial orientation in the localization task.

The BBA suppression effect in CI users also encompasses cortical regions that have been related to speech

recognition, like Wernicke's area. This indicates that CI users have used non-spatial auditory cues to localize the syllables. In other words, it is possible that the implants have differentially transformed the stimuli from different locations. Thus, the observation of stronger BBA suppression in an enlarged postero-dorsal pathway suggests a mutually enhanced stimulus processing in areas that are linked to speech recognition and spatial auditory processing in the speech localization task.

The stimulus-induced suppression of BBA also involved bilateral sensorimotor regions. To avoid confounding motor activity in our study, participants were instructed to conduct a delayed motor response with the left or right index finger following an auditory cue that was presented 700 ms after the onset of the auditory syllables. Whereas there were no motor responses in the analysis interval, it is possible that the BBA suppression in sensorimotor regions reflects the preparation of a motor response. Modulations of BBA suppression have been previously shown in delayed-response paradigms in which auditory vowels served as cues [Kaiser et al., 2001]. Interestingly, BBA suppression during motor planning has been found to increase with increasing response uncertainty [Tzagarakis et al., 2011]. Given that the performance in CI users was lower in the localization task compared with the recognition task, one can assume that they were also more uncertain about the motor response in this task. Thus, uncertainty in motor planning may have contributed to the enhanced BBA suppression in sensorimotor areas. However, motor planning uncertainty does not fully account for effects on BBA suppression in CI users. First, the effect on BBA suppression encompassed areas of the postero-dorsal auditory pathway. Second, the effects on BBA suppression were source-localized particularly to the contralateral stimulation site. Since participants responded with the left or the right index finger, one would have expected to find effects in bilateral sensorimotor cortex. Finally, the effect on BBA suppression remained significant even when the factor task difficulty was included as covariate in the analysis. In addition, the comparison of CI users with best and worst performance did not reveal significant differences in BBA. For these reasons, we consider it unlikely that task difficulty did substantially contribute to the stronger BBA suppression in the localization task in bilateral CI users. Taken together, we suggest that the observed effect on BBA suppression in bilateral CI users reflects an enhanced behaviorally relevant spatial processing of auditory stimuli. This interpretation fits with a recently proposed critical role of the postero-dorsal auditory pathway in sensorimotor processing [Rauschecker, 2011].

While we observed robust suppression of BBA, we did not find substantial modulation of activity in the gamma-band. Previous studies in humans have reported GBA following auditory stimulation [Kaiser et al., 2002a,b], but most of these studies have used MEG. In our EEG study, we have carefully analyzed GBA, including a separate

ICA to specifically remove high-frequency artifacts, but did not find robust modulations in GBA. It is possible that a low signal-to-noise ratio of high-frequency EEG responses to the auditory stimuli has contributed to this finding. Therefore, the absence of gamma-band effects in our study should be interpreted cautiously.

CONCLUSION

Our study provides evidence that adult bilateral CI users, despite periods of deafness and binaural deprivation, process laterally presented auditory syllables in similar pathways as previously reported for normal-hearing adults. A main finding of our study is that the difficulties that bilateral CI users face in an auditory localization task with small ITDs are not reflected in disturbed stimulus processing in the postero-dorsal auditory pathway. Instead, it may be that these difficulties derive from the electrical stimulation protocols of current CIs, which are not accurately translated into neural activity and thereby distort temporal binaural cues. Our finding of intact cortical auditory stimulus processing in CI users also implies that the development of signal processing strategies for preserving unambiguous binaural cues, possibly including binaurally coherent jitter, could improve auditory localization abilities of bilateral CI users.

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