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Consequences of Stimulus Type on Higher-Order Processing in Single-Sided Deaf Cochlear Implant Users

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Keywords

Cochlear implant · Single-sided deafness · Unilateral hearing loss · Event-related potentials · Speech intelligibility · Listening effort

Abstract

Single-sided deaf subjects with a cochlear implant (CI) provide the unique opportunity to compare central auditory processing of the electrical input (CI ear) and the acoustic input (normal-hearing, NH, ear) within the same individual. In these individuals, sensory processing differs between their two ears, while cognitive abilities are the same irrespectively of the sensory input. To better understand perceptual-cognitive factors modulating speech intelligibility with a CI, this electroencephalography study examined the central-auditory processing of words, the cognitive abilities, and the speech intelligibility in 10 postlingually single-sided deaf CI users. We found lower hit rates and prolonged response times for word classification during an oddball task for the CI ear when compared with the NH ear. Also, event-related potentials reflecting sensory (N1) and higher-order processing (N2/N4) were prolonged for word classification (targets versus nontargets) with the CI ear compared with the NH ear. Our results suggest that speech processing via the CI ear and the NH ear differs both at sensory (N1) and cognitive (N2/N4) processing stages, thereby affecting the behavioral performance for speech discrimination. These results provide objective evidence for cognition to be a key factor for speech perception under adverse listening conditions, such as the degraded speech signal provided from the CI.

Introduction

Cochlear Implants (CIs) directly stimulate the auditory nerve and thereby allow their users to hear despite a nonfunctional inner ear. However, sound transmitted through the CI is degraded compared with normal acoustic hearing [Drennan and Rubinstein, 2008], and there is a high variability in speech recognition ability across CI users [Peterson et al., 2010]. Until recently, only patients with profound hearing loss in both ears were considered as CI candidates. In contrast, single-sided deafness (also termed unilateral hearing loss) was a contraindication for CI candidacy. The renewal of the indication criteria for CI surgery in Germany now include persons with single-

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sided deafness and allow these individuals to receive a CI in order to restore binaural hearing [Arndt et al., 2011a, b; Buechner et al., 2010; Deutsche Gesellschaft für Hals-Nasen-Ohren-Heilkunde, Kopf- und Hals-Chirurgie e.V., 2012]. First outcome measures with respect to speech intelligibility in single-sided deaf patients have confirmed that performance significantly improved with a CI compared to monaural acoustic hearing before implantation and compared to other hearing aid systems [Arndt et al., 2011a; Firszt et al., 2012a, b]. Additional benefits after CI switch-on were better sound localization [Kamal et al., 2012; Mertens et al., 2016a; Vlastarakos et al., 2013], the reduction of ipsilateral tinnitus [Arts et al., 2012; Kleine Punte et al., 2013; Mertens et al., 2016a; Punte et al., 2011; Song et al., 2013] and the improvement of quality of life [Härkönen et al., 2015].

CIs are the only available devices which are capable of providing binaural cues in single-sided deafness [Arndt et al., 2011a, b]. However, CI rehabilitation in single-sided deaf patients is still a new topic, and it is important to further understand how rehabilitation can help to optimize the experienced and measured benefit from the CI in these patients. Single-sided deaf CI users greatly differ from *bilaterally* (CI on both ears) or *bimodally* (CI on one ear, hearing aid on the other ear) fitted CI users as their normal-hearing (NH) ear remains the dominant channel of communication. This leads to maximal asymmetric auditory processing [Gordon et al., 2013; Kral et al., 2013]. With respect to speech intelligibility, it is likely that a number of different factors, such as the amount of surviving spiral ganglion cells and the degree of cortical plasticity in the central auditory system, contribute to this variability [Drennan and Rubinstein, 2008; Kral et al., 2016; Nadol et al., 1989; Sandmann et al., 2012, 2015]. So far, studies which have compared the acoustic hearing (NH ear) and the electrical hearing (CI ear) in single-sided deaf CI users have aimed at a better understanding of the pitch perception and the match between cochlear electrode place and acoustic frequency in the cochlea [Schatzer et al., 2014; Vermeire et al., 2008].

Recent studies have suggested that the CI outcome is related to higher-order resources such as verbal abilities or working memory (WM) capacity [Finke et al., 2015, 2016; Kral et al., 2016; Rönnberg et al., 2013]. According to the Ease of Language Understanding model by Rönnberg et al. [2013], WM capacity is needed to support speech understanding via an explicit processing loop in adverse listening conditions, such as listening via a CI. According to this model, one would hypothesize that verbal abilities relate to late event-related potential (ERP) components as well as to the speech intelligibility outcome with the CI [Rönnberg et al., 2008, 2013]. This idea has been supported by our previous study which revealed that the N2/N4 latency of CI users was related to speech perception scores as well as to the subjective listening effort ratings in these individuals [Finke et al., 2016]. However, the previous results have been obtained with bilaterally and bimodally fitted CI users. Until now one can only speculate whether central auditory-cognitive processing (e.g. lexical access or semantic processing) in single-sided deaf CI users shows similar relationships to speech intelligibility and subjective listening effort. Therefore, the present study investigated how speech processing differs between the CI and the NH ear in single-sided deaf CI users and how higher-order processes are related to speech intelligibility with the CI ear in these individuals. Importantly, this particular group of CI users allows a direct comparison of acoustic and CI-mediated processing within the same brain and therefore provides unique insights into the true difference in processing the two different inputs.

We used electroencephalography (EEG) and analyzed ERPs to investigate the central auditory-cognitive processing in single-sided deaf CI users. Similar to previous studies, the neuronal processes underlying speech perception were examined in CI users with an oddball paradigm [Beynon et al., 2005; Finke et al., 2015, 2016; Groenen et al., 2009; Henkin et al., 2009]. In a series of standard syllables or words, infrequent deviant stimuli were intermixed, and participants were asked to respond to these infrequent targets [Polich, 2007]. Typically, a P3 response is elicited to the target stimuli and which has been assumed to represent the stimulus evaluation and classification process [Polich, 2007]. The N2 and the N4 are two cortical responses which been associated with lexical information access and semantic categorization [Brink and Hagoort, 2004; Deacon et al., 1991; Polich, 1985; Schmitt et al., 2001; van den Brink et al., 2001]. However, differentiating the N2 clearly from the N4 is not trivial, and previous studies show contradictory results. Some studies could clearly distinguish the components from each other [Deacon et al., 1991; van den Brink et al., 2001] while other studies suggest that it is likely that the N2 is not distinct from the N4 [Brink and Hagoort, 2004; Polich, 1985]. With regard to CI users, lexical information access (reflected by N2/N4 latency) and word classification (reflected by P3 latency) were found to be delayed when compared to NH listeners [Beynon et al., 2005; Finke et al., 2016; Henkin et al., 2009, 2014]. Thus, speech perception in adverse listening conditions seems to be influ-

Table 1. Summary of participant characteristics

CI user	Age, years	CI side	Implant/processor	Etiology	Cause of deafness	Duration of deafness, years	CI use, months	HSM quiet, %	HSM noise, %	FB, %	Mean hearing loss, dB
CI01	64	right	Concerto Flex 28	unknown	SHL, Ménière disease	9	34	74.5	45.2	60	7.5
CI02	54	left	Concerto Flex 28	acute	SHL	10	17	83	24	60	11.25
CI03	40	left	Sonata ti100	acute	SHL	1	53	44.3	0	30	3.75
CI04	68	right	Sonata ti100	acute	SHL	7	64	13.2	0	10	35
CI05	50	left	Synchrony Flex 28	progressive	SHL	8	7	100	62	85	3.75
CI06	26	right	Concerto Flex 28	acute	unknown	1	8	100	47	60	–2.5
CI07	53	left	Concerto Standard	acute	ototoxic	23	33	95.3	58	55	6.25
CI08	68	left	Concerto Standard	acute	unknown	1	18	31	–	15	12.5
CI09[a]	51	left	Sonata ti100	acute	stapedectomy	unknown	67	42.5	0	45	20
CI10	55	right	Concerto Flex 28	progressive	unknown	6	29	100	75	100	10
CI11	56	left	Sonata ti100	acute	SHL	3	65	70	44	75	3.75

HSM, Hochmair-Schulz-Moser sentence test; FB, Freiburg Monosyllabic Word test; SHL, sensorineural hearing loss.
[a] User CI09 was excluded from further analyses.

enced by higher-order processes as well as by verbal WM capacity and lexical abilities, and may be affected by phonological processing as well [Akeroyd, 2008; Andersson, 2002; Banks et al., 2015; Benard et al., 2014; Lunner, 2003; Lyxell et al., 1998; Rönnberg et al., 2013; Rudner et al., 2008; Zekveld et al., 2007a, b].

It can be assumed that speech perception performance in single-sided deaf CI users is mainly limited due to the degraded speech quality transmitted via the CI. Previous work has shown that the phonological processing in CI users can change during the time of deafness [Classon et al., 2013; Lazard et al., 2010]. It is reasonable to assume that the quality and precision of phonological representations in long-term memory should not change during the duration of deafness in patients with single-sided deafness due to the remaining NH ear [Rönnberg et al., 2008, 2013]. On the other hand, it is likely that more cognitive resources (e.g. WM) are needed for hearing with one ear [Rönnberg et al., 2008, 2013]. After implantation, single-sided deaf CI users need (1) to adapt to the degraded input provided by the CI ear and (2) to match the NH ear and the CI ear with their very distinct signal quality to their phonological representation. It is therefore important to investigate whether and how higher-order resources contribute to speech intelligibility with the CI in single-sided deaf CI users and how neuronal processes underlying speech perception might differ between the CI and NH ear. This approach can help us to better understand the differences in speech perception between acoustic and electrical hearing in single-sided deaf CI users.

Materials and Methods

Participants

Eleven single-sided deaf CI users (6 females, 5 males) participated in the study. The participants had normal or corrected-to-normal vision, were postlingually deafened and did not use sign language for communication. One subject (CI09) was excluded from further analyses as he was unable to understand speech with his CI alone. None of the participants had a history of neurological disease. All participants had been using their CI continuously for at least 6 months and had been deaf for an average of 9.5 ± 8.6 years. All participants were unilaterally implanted. Normal hearing was verified by pure-tone audiometry with a mean hearing loss (average over 0.5, 1, 2, and 4 kHz) of less than 30 dB (except for 1 participant who was 68 years old and had 35 dB mean hearing loss). See Table 1 for further information with respect to clinical history, individual hearing loss, and the speech intelligibility tests Hochmair-Schulz-Moser sentence test in quiet and noise and the Freiburg Monosyllabic Word test.

Participants gave informed written consent before the experiment. The experimental protocol was approved by the ethical committee of the Hannover Medical School and was in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Task and Procedure

Participants were tested with an auditory oddball paradigm with a target probability of 20% [Finke et al., 2016; Polich, 2007]. Each trial consisted of a disyllabic German noun (800 ms long), and participants had to identify it as a living or nonliving entity (Fig. 1). Targets were defined as words describing living entities (persons or animals). Participants were asked to press a button with their right thumb within 1,700 ms of hearing a target word. We used the same stimuli and word lists as in our previous work. These consisted of 7 target words and 28 nontarget words which were pseudo-randomly repeated 10 times. Targets were separated by at least 2 nontargets and a maximum of 7 nontargets (mean =

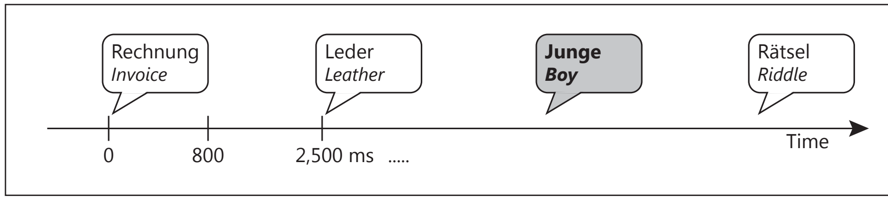

Fig. 1. Overview of the experimental procedure. Adapted from Finke et al. [2016].

3.8). After participants had completed a short training block to familiarize themselves with the task, 70 targets were presented for each ear. The order of the presentation was held constant. After a training block to familiarize the participants with the test set-up and the task, we tested the CI ear and the NH ear consecutively. This followed the rationale that according to our clinical experience, fatigue effects occur much more strongly for listening with the CI compared to acoustic hearing. This particularly applies to single-sided deaf CI users whose NH ear is thought to remain the dominant channel for communication. To avoid confounding effects by fatigue, we decided to test the CI ear before the NH ear. In particular, the direct audio input level to the speech processor was calibrated to match sound input delivered to the processor acoustically at a level of 65 dB SPL. Target and nontarget stimuli were matched regarding their word frequency in German according to the "Leipziger Korpus" (http://wortschatz.uni-leipzig.de/). Also the morphological complexity was kept constant by balancing the amount of derived and nonderived words in the two stimulus classes [Finke et al., 2016]. The stress assignment was on the penultimate syllable for all words, which is the default stress pattern in German [Féry, 1998; Wiese, 2000].

Prior to the EEG recording, participants completed three tests. The selection of nonauditory tests followed the principle of minimizing effects of audibility and auditory spoken language processing [Kronenberger et al., 2013b]. Therefore, none of the cognitive tests applied in the current study relied on auditory input.

The "Mehrfachwahl-Wortschatz-Intelligenz-Test" (MWT-B), a vocabulary intelligence test that measures how well participants recognize words on the basis of the written word form was used [Lehrl, 1999]. In this test, participants have to choose the only real word from a list of 5 words. Regarding the verbal fluency test, the subtest "lexical fluency" from the "Regensburger Wortflüssigkeitstest" was applied [Aschenbrenner et al., 2000]. Here, the participants' task was to orally report as many nouns starting with the letter "S" as possible within 2 min. Finally, verbal WM capacity was measured with a German version of the size comparison span (SICSPAN) test [Finke et al., 2016; Sörqvist et al., 2010].

In situations where speech perception is difficult (such as speech in noise or interrupted speech), we strongly rely on cognitive and linguistic processes [Zekveld et al., 2010]. In these situations, speech is not processed automatically but explicitly needs additional cognitive resources [Rönnberg et al., 2013; Zekveld et al., 2010]. There is evidence that endogenous ERP components such as the N2/N4 and the P3 can be indicators of how easy or hard a listening condition is, and that these components relate to listening effort [Finke et al., 2016; Igelmund et al., 2009]. In the present study, the participants were asked to rate their listening effort during the EEG recording for each ear (CI, NH) separately after the corresponding block. Specifically, the participants were asked to mark their listening effort to understand the words on a printed 5-point scale ranging from "not difficult at all" (1), "a bit difficult" (2), "difficult" (3), "very difficult" (4) to "I cannot understand the words" (5).

Data Recording and Analysis

Verbal Ability Data and Listening Effort

The MWT-B and the Regensburger Wortflüssigkeitstest were analyzed according to the official guidelines provided with the test material. As suggested by Sörqvist et al. [2010], the results of the SICSPAN test were analyzed in two different ways: first, by taking the total sum of correctly remembered words and second, by counting the maximum number of remembered items within one block. The difference in listening effort between the CI and the NH ear was analyzed with the Wilcoxon signed-rank test.

Behavioral Data

For behavioral analysis, a correct trial was defined as a button press that occurred between 100 and 1,700 ms after target word onset. Response times (RTs) as well as hit rates were compared between both ears. A paired t test was used for the RT but a Wilcoxon signed-rank test to analyze the difference in hit rate as the accuracy data was not normally distributed (tested with Kolmogorow-Smirnow test). Significance was determined at an alpha level of 0.05 for all analyses, and partial eta square was reported as a measure of effect size.

Electrophysiological Data

EEG was continuously recorded by a SynAmps amplifier (Neuroscan, Compumedics, Charlotte, NC, USA) from 81 scalp electrodes using a 128-channel Quik-Cap (Neuroscan, Compumedics). The electrodes were placed according to the 10-10 system. Over parietal scalp regions 7 additional electrodes were used to have more information from scalp regions where task-related (P3) effects were expected. Two additional electrodes were placed at the left and the right mastoid. The common reference electrode was placed at the tip of the nose. Moreover, eye movements were measured with 2 bipolar electrodes placed above and below the right eye (vertical electro-oculogram) and 2 bipolar electrodes placed at the outer canthi of each eye (horizontal electro-oculogram). The EEG was recorded at 1 kHz, and electrode impedances were kept below 20 kΩ during the whole recording session.

EEG data were analyzed with MATLAB (R2011b; Mathworks, Natick, MA, USA) and EEGLAB 11.0.5.4.b [Delorme and Makeig, 2004]. The raw data were downsampled to 500 Hz, offline highpass filtered at 1 Hz, and epoched into segments from –200 to 1,200 ms relative to auditory stimulus onset. Epochs containing unique, nonstereotype artifacts were removed. Subsequently, an independent component analysis was computed on the remaining epochs

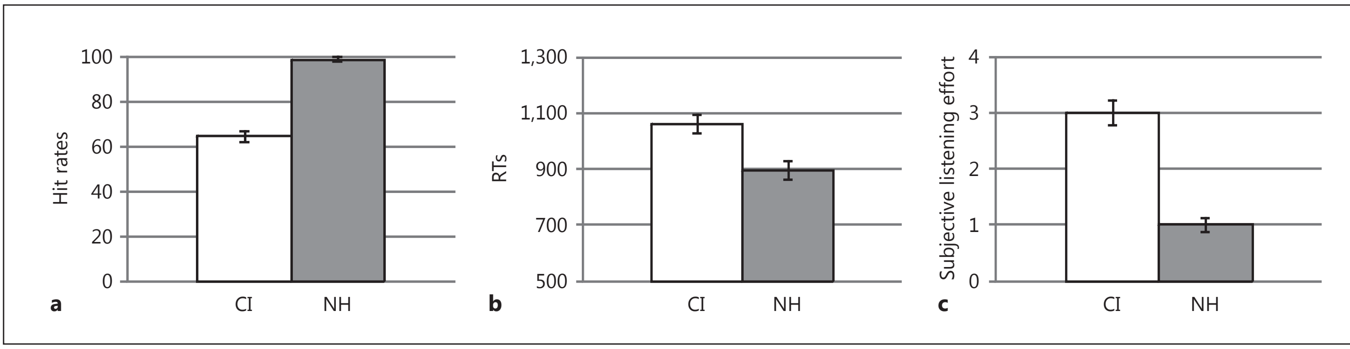

Fig. 2. Decreased hit rates (**a**) and increased RTs (**b**) were found for word classification with the CI ear compared to the NH ear. **c** The subjectively rated listening effort was enhanced when listening via the CI. Error bars denote the standard error of the mean.

[Bell and Sejnowski, 1995]. The resulting independent component analysis weights were applied to newly filtered (0.1–30 Hz) and epoched raw data. Independent components reflecting eye blinks, horizontal eye movements, and CI artifacts were removed [Jung et al., 2000a, b]. Components representing CI artifacts were identified by the centroid on the side of the implanted device and by the time course of component activity, which typically showed a sharp onset around 30 ms after stimulus onset (for details about the reduction of CI artifacts by means of independent component analysis, see Debener et al. [2008], Sandmann et al. [2009], and Viola et al. [2011]). Then, missing channels located in proximity to the speech processor and transmitter coil were interpolated using spherical spline interpolation (mean number of missing electrodes: 6.3; SD: 2.11; range: 3–10 [Perrin et al., 1989]). Only correct trials (hits for target stimuli; correct rejections for nontarget stimuli) were included for further analyses. Finally, auditory ERPs for targets and nontargets were obtained by averaging over trials and subtraction of a baseline –200 to 0 ms prior to the stimulus.

ERP analysis included the N1 to investigate the audiosensory processing and the N2/N4 as well as the P3 to investigate the auditory-cognitive processing of speech sounds [Finke et al., 2016; Henkin et al., 2009, 2014]. The analyses were performed on single-subject averages for a frontocentral (N1 peak), a central (N2/N4 peak), and a parietal (P3 peak) region of interest (ROI). The respective ROIs included the channels with the largest deflections observed in the grand average. The ROI for the N1 component included Fz, FCz, FC1, FC2, Cz, F1, F2, CPPz; for the N2/N4 component, Cz, FCz, FC1, FC2, CPPz, C1, C2, CP1, CP2 were included and for the P3 component, POO7, POO3, POO4, POO8, POz, PO3, PO2, PO4, P3, PPO1, PPO2, P4, PPOz. ERPs were quantified as the signed area under the curve [Luck, 2014] by computing the positive (P3) and the negative (N1, N2/N4) area under the ERP waveform over the given latency range. In general, latency ranges for ERP amplitude and latency detection were defined on the basis of the grand average computed across all conditions and participants. The ERP latency was quantified by means of the 50% area latency measure as follows. We computed the signed area under the ERP waveform over a given latency range and then defined the time point that divides that area into one half. The use of the area amplitude and latency measures is advantageous to the more conventional peak amplitude measure because it is a linear measure that is less influenced by single-trial latency jitter, and it is relatively insensitive to high-frequency noise [Luck, 2014; Meyer et al., 2011; Petermann et al., 2009].

Statistical analysis of all peaks (N1, N2/N4) focused on the respective ROIs (frontocentral: N1; central: N2/N4; parietal: P3). Area amplitudes and latencies of the N1 and N2/N4 ERP were subjected to separate repeated-measures ANOVAs, with targetness (targets, nontargets) and ear (CI, NH) as within-subject factors. Greenhouse-Geisser correction was applied to compensate for violations of the sphericity assumption. In general, significant main effects and interactions ($p < 0.05$) in the ANOVAs were followed up with post hoc *t* tests (Bonferroni correction).

Results

Behavioral Results and Listening Effort

Participants' percentile ranks ranged from 29.2 to 94.3% in the MWT-B test (mean: 54.33; SD = 19.6). For the Regensburger Wortflüssigkeits-Test, the percentile scores ranked between 3 and 52 (mean = 25.88; SD = 17.17). The total number in remembered words in the SICSPAN was on average 30.5 (SD = 6.2; range = 22–55). The SICSPAN and Regensburger Wortflüssigkeits-Test results go well in line with data from NH participants and bimodally/bilaterally fitted CI users in our previous study which revealed no difference between the 2 groups [Finke et al., 2016]. Participants' mean MWT-B score was more similar to the NH group than to the CI group in this study.

Median RTs, hit rates, and the subjectively rated listening effort during the oddball task are displayed for both, the CI and the NH ear in Figure 2. RTs were longer when words were presented via the CI (1,059 ms) than to the NH ear (895 ms). A paired *t* test revealed significant

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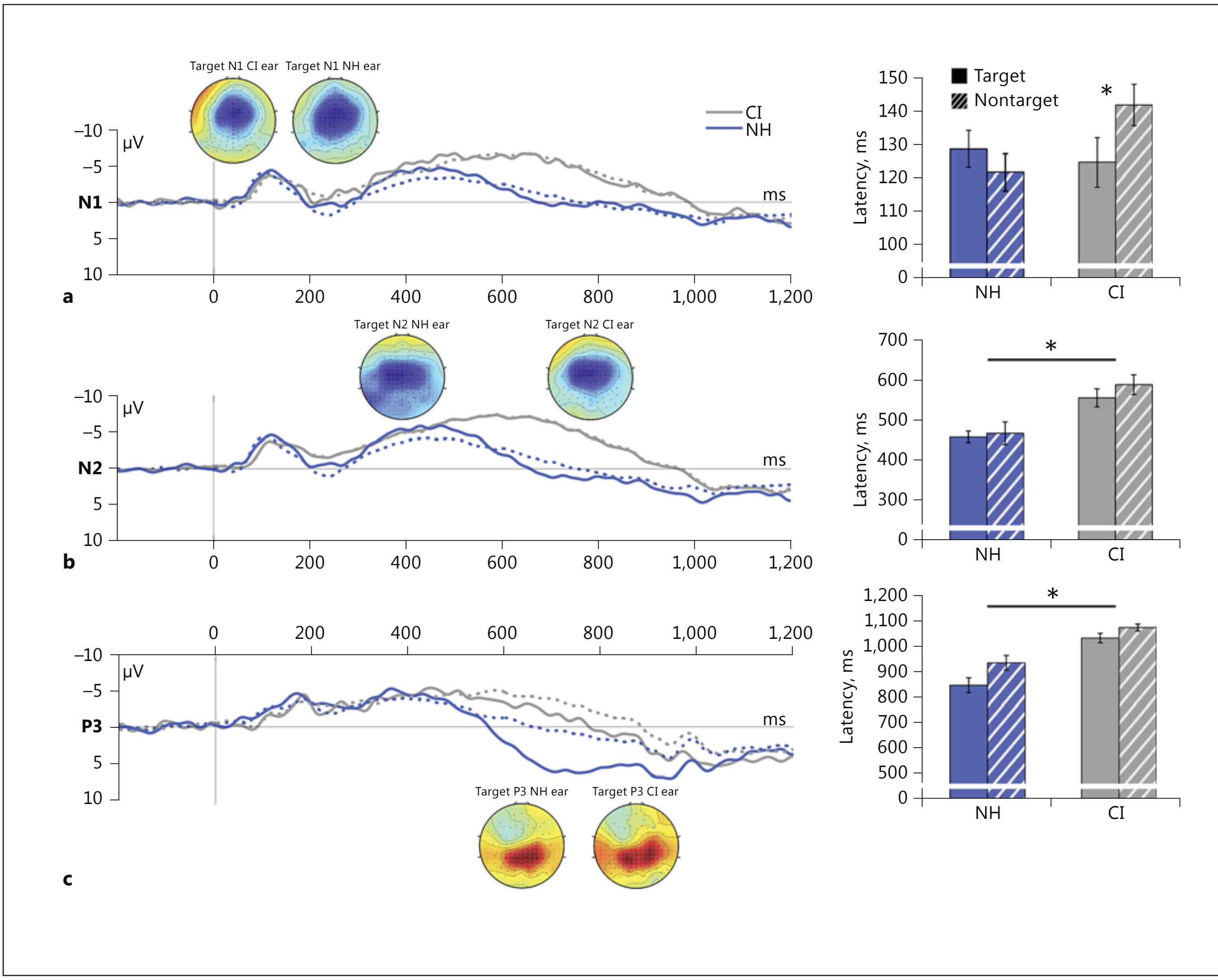

Fig. 3. ERP waveforms for the CI ear (gray; colors in the online version only) and NH ear (blue) for the N1 (**a**, frontocentral ROI), N2/N4 (**b**, central ROI), and P3 (**c**, parietal ROI). ERPs elicited by targets are displayed by solid lines, ERPs elicited by nontarget stimuli by dotted lines. Latencies of the respective ERP components are shown as bar graphs on the right.

differences in RTs between word processing with the CI compared to the NH ear [$t(9) = 6.171$; $p < 0.001$]. The hit rate for the CI ear ranged between 55.7 and 81.5% (mean = 65.1 ± 8%) but it was almost perfect with the NH ear (96.9 ± 3.1%). As the hit rate was not normally distributed, data were statistically analyzed with a Wilcoxon signed-rank test. This revealed significant differences in the hit rates for words presented via the CI compared to the NH ear ($Z = -2.81$; $p = 0.005$). Further, the subjective ratings of listening effort in the CI and the NH ear were compared with a Wilcoxon signed-rank test. Speech perception with the CI was rated as significantly different compared to the NH ear ($Z = -2.879$; $p = 0.004$; $median_{NH} = 1$; $median_{CI} = 3$).

Event-Related Potentials

The grand averages of the NH and CI ear showed ERPs with maximal deflections at N1 latency (NH ear: 125.3 ms; CI ear: 133.4 ms), N2/N4 latency (NH ear: 463.9 ms; CI ear: 573.7 ms) and P3 latency (NH ear: 891.9 ms; CI ear: 1,052.4 ms). Results are illustrated in Figure 3.

Sensory Processing

Our data did not reveal any differences in the N1 amplitude for the factors ear or targetness. However, we found a significant targetness × ear interaction for the N1 latency [$F(1, 9) = 5.97$; $p = 0.037$, $\eta p^2 = 0.399$]. The paired t test revealed shorter N1 latencies for the targets compared to the nontarget words for the CI ear [$t(9) = 3.73$; $p = 0.004$] but no difference between the stimuli for the NH ear.

Higher-Order Processing

The N2/N4 latency for the CI ear was prolonged compared to the NH ear as indicated by a significant main effect of the factor ear [$F(1, 9) = 74.85$; $p < 0.001$; $\eta p^2 = 0.893$]. Also, the amplitude area revealed a main effect of ear [$F(1, 9) = 46.11$, $p < 0.001$; $\eta p^2 = 0.837$]. The area for the CI ear was significantly larger than for the NH ear. No differences in N2/N4 latency or area amplitude were found for the factor targetness.

For the analysis of the P3 latency, a significant main effect of targetness was found [$F(1, 8) = 18.32$; $p = 0.003$; $\eta p^2 = 0.69$]. The P3 elicited by targets occurred earlier compared to nontarget words. Further, the main effect of ear was significant [$F(1, 8) = 27.27$; $p = 0.001$; $\eta p^2 = 0.773$] due to an earlier P3 peak in the NH ear as compared to the CI ear. P3 amplitudes were analyzed using a Wilcoxon signed-rank test which revealed a significantly larger area amplitude for the NH ear compared to the CI ear ($Z = -2.073$; $p = 0.038$].

Based on previous results, we hypothesized that the ERP latencies (particularly the N2/N4) for the CI ear would be related to listening effort and speech intelligibility scores [Finke et al., 2016]. We therefore performed such correlational analyses also for the present data. However, no significant relationships between auditory-cognitive processing (N2/N4) and listening effort or speech intelligibility tests were found (all $p > 0.05$).

Discussion

The present study revealed differences in speech processing for the CI ear when compared with the NH ear in single-sided deaf CI users. For word classification in the oddball task, the CI input resulted in lower hit rates and prolonged response times. This corresponded to the objective ERP measures, pointing to differences in sensory (N1) and higher-order processing (N2/N4) for word classification with the CI ear when compared with the NH ear. Our results indicate that speech processing via the CI ear is prolonged compared to the NH higher-order processing stages (N2/N4) as well as in behavioral response times. Importantly, the within-subject design allowed us to intraindividually compare the differences between acoustic and electric hearing which helps to improve our understanding of factors contributing to the CI outcome. Our data suggest that speech processing via the CI ear differs from the processing via the NH ear not only at the early perceptual, but also at higher-order processing stages. Since this result was obtained in the same individuals, it is likely that higher-order processing differences are downstream effects of the stimulus type (CI vs. normal hearing), most likely related to the need of top-down restoration and increased listening effort for listening with the CI. These results have implications also beyond single-sided deafness. They demonstrate the significant contribution of top-down (cognitive) processing to the understanding of CI signals in general.

Behavioral Results

The behavioral results from the oddball task showed lower hit rates and prolonged RTs when words were presented via the CI compared with the NH ear. This confirmed previous observations of poorer auditory discrimination and speech intelligibility in CI users than in NH listeners [Finke et al., 2016; Sandmann et al., 2015]. The impaired performance with a CI can be explained by the limited spectral and temporal information transmitted by the CI and the spread of electrically evoked neuronal excitation in the cochlea [Drennan and Rubinstein, 2008]. Finally, physiological deficiencies [Nadol et al., 1989] and central reorganizations induced by auditory deprivation may contribute to limited hearing abilities after implantation [Kral et al., 2016; Sandmann et al., 2012].

Event-Related Potentials

N1 latencies were longer when words were presented via the CI ear compared to the NH ear, particularly for nontarget stimuli. This confirms previous research which reported differences in the sensory processing of auditory stimuli in CI users and NH listeners [Finke et al., 2015; Finke et al., 2016; Oates et al., 2002; Sandmann et al., 2009, 2010, 2015].

Foremost, the present study aimed at investigating higher-order processing that underlies speech recognition in single-sided deaf CI users. Due to the degraded signal provided by the CI ear, we expected prolonged higher-order processing for words presented via the CI than words presented acoustically via the NH ear. Consistent with our hypothesis, our data revealed longer N2/

N4 and P3 latencies for speech processing in the CI ear than in the NH ear. The use of different words enforced participants to fully retrieve the words' meaning from their mental lexicon. This process of semantic classification seems to be reflected by the N4 component [Brink and Hagoort, 2004; Deacon et al., 1991; Polich, 1985; van den Brink et al., 2001]. With our data it is not possible to prove whether the late negativity that we refer to as N2/N4 is exclusively an N2 or an N4 component. Nevertheless, our finding of prolonged N2/N4 latency suggests that lexical information access is slower when auditory input is degraded and only partially matches the attributes of lexical representations stored in long-term memory as suggested by Rönnberg et al. [2013]. Our data correspond to the idea proposed by the Ease of Language Understanding model and suggest that additional explicit processing seems to be required due to the limited information transmitted by the CI [Finke et al., 2015, 2016].

As mentioned in the Method section, we tested the CI ear first to avoid fatigue effects which occur more strongly for listening with the CI compared to acoustic hearing. Thus, the CI ear was tested under best conditions. Although a bias due to other experimental influences might be possible, our results from an intraindividual comparison confirmed previous observations of longer N2/N4 and P3 latencies in CI users when compared to NH listeners [Beynon et al., 2005; Finke et al., 2016; Friesen et al., 2009; Henkin et al., 2014].

Importance of Within-Subject Comparisons

So far, studies which aimed at better understanding the effects of degraded speech have compared CI users with a group of matched NH listeners [Beynon et al., 2005; Finke et al., 2016; Henkin et al., 2009]. Alternatively, they have used vocoded speech to simulate CIs in NH participants [Friesen et al., 2001, 2009]. Nonetheless, the studies comparing CI users with NH participants listening to vocoded sounds found group differences in the neuronal processing of auditory stimuli [Rouger et al., 2007; Sandmann et al., 2010]. This indicates that, (1) a CI input does not sound to CI listeners like vocoded speech to NH listeners [Newman and Chatterjee, 2013] and that (2) a direct (within-subject) comparison of speech processing and the related listening effort between acoustic and electric hearing should be of great interest to better understand the impact of degraded speech on speech intelligibility in CI users. To date, our present study is the first which intraindividually compares neuronal processes underlying speech processing in single-sided deaf CI users. The importance of a better understanding of cortical reorganization in single-sided deaf CI users and the resulting opportunities in rehabilitation and hearing outcome have been shown in a recent ERP study [Sharma et al., 2016]. Our results add to the clinical and scientific discussion of single-sided deafness and its treatment with CIs as they extend the understanding of differences between speech processing in electric and acoustic hearing.

On the Relationship between Central Auditory Processing, Verbal Abilities, and Speech Intelligibility

Several studies have previously shown that the brain reorganizes during the time of sensory deprivation. However, differences between CI users and NH listeners have not only been found in sensory, but also auditory-cognitive processing stages [Finke et al., 2015, 2016; Giraud and Lee, 2007; Giraud et al., 2001; Kral and Sharma, 2012; Kral et al., 2016; Kronenberger et al., 2013a; Lazard et al., 2010; Lyxell et al., 1996, 1998; Pisoni, 2000; Pisoni et al., 2011; Rönnberg et al., 2013; Sandmann et al., 2012, 2015]. Previous studies with NH listeners and hearing-impaired listeners have emphasized the role of WM and verbal abilities for speech intelligibility in adverse listening conditions [Akeroyd, 2008; Banks et al., 2015; Benard et al., 2014; Kronenberger et al., 2013a, b; Obleser and Kotz, 2011; Rönnberg et al., 2013]. It is plausible to assume that WM and verbal abilities play an important role for speech intelligibility in CI users as well. In contrast to our expectations, our present results did not show correlations between the auditory-cognitive processing, verbal abilities and speech intelligibility. Such relations were found in our previous study with bimodal and bilaterally fitted CI users [Finke et al., 2016]. The lack of a replication of such results might be caused by the small sample size or due to the fact that single-sided deaf CI users differ in this respect from other CI users. Given that our intraindividual data only partially replicate previous results from between-group comparisons [Finke et al., 2016], more research is certainly warranted to better understand how central-auditory processing, verbal abilities and speech intelligibility relate to each other in different groups of CI users.

Possible Clinical Implications

The indication criteria in Germany for CI candidates have changed some years ago. Nowadays, patients with single-sided deafness are offered to receive a CI [Arndt et al., 2011b; Buechner et al., 2010; Deutsche Gesellschaft für Hals-Nasen-Ohren-Heilkunde, Kopf- und Hals-Chirurgie e.V., 2012]. Germany is one of the few countries in which regulatory approval and reimbursement schemes for CI treatment are in place for this type of patients.

In our study, both the sensory and cognitive processing components were different for the CI ear when compared with the NH ear. While the early components were slightly smaller for the CI, corresponding to degraded sensory input, the late components were larger for the CI ear, demonstrating that the degraded signal provided by the CI needed to be restored by higher-order, top-down processing [Banks et al., 2015; Benard et al., 2014; Lyxell et al., 1998]. This is interesting, since it provides evidence that the difference in the processing is not only at the acoustic and phonetic processing levels – which in principle could be sufficient if the sensory input was clear enough. It has been suggested that for the decoding of CI speech, the long-latency cognitive processing contributes significantly to the understanding of the CI input [Finke et al., 2016; Lunner, 2003; Rönnberg et al., 2013]. The brain activates higher-order resources to reconstruct the speech signal, accessing the syntactic and semantic level to allow phonemic reconstruction in the "gaps" of the degraded speech signals [Banks et al., 2015; Benard et al., 2014; Kral et al., 2016; Rönnberg et al., 2013]. A behavioral correlate of such cognitive downstream effects of degraded speech would be higher subjective listening effort and slowed speech processing [Kral et al., 2016; Lunner, 2003; Rönnberg et al., 2013; Rudner et al., 2008; Zekveld et al., 2007a]. This was observed in the behavioral part of this study. However, one has to keep in mind that the sample presented here consists of only 10 individuals with heterogeneous etiology and clinical history. Relations between the tested variables might be present but not (statistically) apparent due to the small sample size. Thus, more behavioral and electrophysiological data of speech intelligibility and speech processing in CI users are certainly warranted to replicate present results and to further explore the impact of (single-sided) deafness before surgery and factors contributing to CI performance in these patients.

Conclusions

Our results suggest that listening with a CI leads to a slower access to lexical information and prolonged word evaluation. It has been hypothesized that a mismatch between the limited CI input and the word representation stored in the long-term memory makes speech perception prolonged and more effortful [Rönnberg et al., 2013]. Our data correspond to this idea. The observed differences in sensory and auditory-cognitive processing of words between the CI ear and the NH ear are likely due to the differences in signal quality (acoustic vs. electric hearing). The prolonged N2/N4 component may be a neuronal correlate of listening effort [Finke et al., 2016].

Previous studies have shown individual differences in the adaption to vocoded speech in NH participants, indicating that differences in cognitive abilities can cause discrepancies in speech perception in adverse listening conditions. Our data indicate that auditory-cognitive processing is prolonged in CI users. It is plausible to assume that this prolongation is related to the degraded CI signal, making it difficult to match the sensory input with the word representation stored in the long-term memory. Despite the lack of correlations with verbal abilities in the present study, one might contemplate whether lexical access and semantic processing can be trained and in turn not only improve speech intelligibility with the CI, but also make it less effortful.

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Disclosure Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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