Clinical Neurophysiology 129 (2018) 133–142

Contents lists available at ScienceDirect

Clinical Neurophysiology

journal homepage: www.elsevier.com/locate/clinph

Event-related neuronal responses to acoustic novelty in single-sided deaf cochlear implant users: Initial findings

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ARTICLE INFO

Article history:
Accepted 31 October 2017
Available online 7 November 2017

Keywords:
Cochlear implants
Event-related potential
Oddball paradigm
Novelty-P3

HIGHLIGHTS

- Neuronal sound processing was investigated in single-sided deaf cochlear implant (CI) users with a three-stimulus oddball paradigm.
- Auditory processing differs in sensory and higher order processing between the normal hearing and the CI ear.
- CI degeneration attenuates early, but not late Novelty-P3 amplitudes.

ABSTRACT

Objective: A cochlear implant (CI) is an auditory prosthesis restoring profound hearing loss. However, CI-transmitted sounds are degraded compared to normal acoustic hearing. We investigated cortical responses related to CI-degraded against acoustic listening.

Methods: Event-related potentials (ERPs) were recorded from eight single-sided deaf CI users who performed a three-stimulus oddball task, separately with their normal hearing ear and CI ear. The oddball tones were occasionally intermitted by novel sounds. ERP responses were compared between electric and acoustic listening for the auditory (N1) and auditory-cognitive (Novelty P3, Target-P3) ERP components.

Results: CI-degraded listening was associated with attenuated sensory processing (N1) and with attenuated early cortical responses to acoustic novelty whereas the late cortical responses to acoustic novelty and the target-P3 did not differ between NH and CI ears.

Conclusion: The present study replicates the CI-attenuation of Novelty-P3 amplitudes in a within-subject comparison. Further, we show that the CI-attenuation of Novelty-P3 amplitudes extends to early cortical responses to acoustic novelty, but not to late novelty responses.

Significance: The dissociation into CI-attenuated P3 early Novelty-P3 amplitudes and CI-unaffected late Novelty-P3 amplitudes represents a cortical fingerprint of CI-degraded listening. It further contributes to general claims of distinct auditory Novelty-P3 sub-components.

1. Introduction

Cochlear implants (CIs) can restore hearing to deaf and severely hard of hearing individuals. They bypass a non-functional inner ear by direct electrical stimulation of auditory nerves (Zeng et al., 2011). Compared to normal acoustic hearing CI-transmitted sounds are degraded (Drennan and Rubinstein, 2008). This makes speech understanding difficult, particularly in background noise

Abbreviations: CI, cochlear Implant; NH, normal hearing; ERP, event-related potentials; nP3E, early Novelty-P3; nP3L, late Novelty-P3; HL, hearing loss; ELU, ease in language understanding model; SNR, signal-to-noise ratio; SPL, sound pressure level; EEG, electroencephalogram; RWT, Regensburger Wortflüssigkeits-Test; MWT-B, Mehrfach-Wortsschatz-Test; SICSPAN, size comparison test; RT, response time; HR, hit rate; EOG, electrooculography; ICA, independent component analysis; ROI, regions of interest.

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https://doi.org/10.1016/j.clinph.2017.10.025
1388-2457/

(Baskent et al., 2016; Wilson and Dorman, 2008). Speech intelligibility with the CI is typically assessed via word or sentences tests in quiet or noise (Hahlbrock, 1953; Haumann et al., 2010; Hey et al., 2014, 2016; Hochmair-Desoyer et al., 1997; Zeng and Fay, 2013). Event-related potentials (ERPs) are not part of routine clinical aftercare for CI patients, although they provide measures of cortical activities with high temporal resolution (Luck, 2014). ERPs may serve as an index of central auditory-cognitive processing that results from CI-transmitted input compared to normal acoustic input (Billings et al., 2011; Finke et al., 2016a, 2016b; Henkin et al., 2002, 2009; Luck, 2014).

Rönnberg et al. (2013) proposed a cognitive model of speech understanding, which emphasizes interactions among working memory, related executive functions, semantic and episodic long-term memory. The Ease of Language Understanding (ELU) model asserts that top-down attention, working memory, bottom-up phonological and linguistic processing interact at different levels in the auditory system (Rönnberg et al., 2013, 2016). In ideal listening conditions automatically encoded attributes of the acoustic input trigger rapid and implicit access to the mental lexicon. In contrast working memory supports retrieval from the mental lexicon through filling in or inferring missing pieces of information in an iterative process in adverse listening situations (e.g. speech in noise or sound transmitted via a CI).

ERP signatures of acoustic novelty may serve as a paradigmatic model for studying these interactions between bottom-up and top-down processing at the cortical level of the auditory system (Friedman et al., 2001). The late (cognitive) ERP P3 is decomposable into separable sub-components (Polich, 2007). The standard for studying the so called target-P3 is the two-stimulus oddball task, which consists of a classification between frequent standard stimuli and rare target stimuli. The Target-P3 is a neural correlate of those cognitive processes, which are recruited for the evaluation of the stimuli according to the classification rule of the particular oddball task (Luck, 2014; Polich, 2007). The attended novelty oddball task includes an additional class of trial-unique novel stimuli. They are irrelevant to the categorization task at hand and elicit an anterior Novelty-P3. The Novelty-P3 is traditionally thought to reflect attentional processes related to the orienting response (Friedman et al., 2001; Lange et al., 2015; Polich, 2007). Principal component analysis (PCA) have confirmed the characteristic midline fronto-central topography of the Novelty-P3 (Spencer et al., 2001), with the anterior cingulate cortex as a neural generator (Debener et al., 2005; Dien et al., 2003). A large PCA study (Tenke et al., 2010) yielded a two-component solution for the auditory Novelty-P3, which is also consistent with findings from other studies (Escera et al., 1998; Yago et al., 2003). Specifically, an early vertex Novelty-P3 (nP3E) was present for novels, but not targets. The functional roles of the nP3E and nP3L components are still a matter of debate (Barry et al., 2016; Bidet-Caulet et al., 2015). It has been proposed that the nP3E reflects novelty detection (Yago et al., 2003) or an alerting operation (Čeponienė et al., 2004), and these processes may be automatically elicited by bottom-up signals from novel stimuli. In contrast, the nP3L has been associated with the orienting of attention towards novel sounds as well as with context updating operations or subsequent working memory storage (Friedman et al., 2001; Polich, 2007; Yago et al., 2003). These processes may be controlled by top-down signals from task demands.

Table 1 summarizes the to our knowledge published ERP studies that examined the auditory P3 in CI users. All studies relied on comparisons between CI users and normal hearing individuals samples with $N < 20$ with Torppa et al. (2012) as an exception. The majority of the available studies relied on two-stimulus oddball tasks, and focused on the Target-P3. The results that were obtained from these studies are partially inconsistent across studies. Ten out of 20 experimental comparisons, using an oddball paradigm yielded prolonged auditory Target-P3 latencies in CI users, and nine out of 23 experimental comparisons yielded attenuated auditory Target-P3 amplitudes in CI users. When comparing these different studies, it should be kept in mind, that different stimuli are used for the oddball task (i.e. speech or speech-like stimuli, and tonal stimuli) as well as different measures (amplitudes and/or latencies) were analyzed. Taken together, the available Target-P3 data remained rather inconclusive regarding potential links between CI-degraded listening and potential changes in neural correlates of cognitive processes for task-related stimulus evaluation. The available Target-P3 data remain rather inconclusive regarding potential links between CI-degraded listening and potential changes in neural correlates of cognitive processes for task-related stimulus evaluation. Only two studies looked at the auditory Novelty-P3 in CI users (Finke et al., 2015; Nager et al., 2007). Both studies yielded evidence that CI-degraded listening is associated with attenuated Novelty-P3 amplitudes. Clearly, more evidence is needed to better understand whether and how the CI-degraded input is associated with changes in the cortical activity for auditory cognition mirrored in the Novelty-P3. With the present study, we also extend the idea of the ELU model to a non-linguistic listening task. The oddball paradigm allows to distinguish between top-down und bottom-up processing (Escera et al., 1998; Polich, 2007). We predict that CI-transmitted hearing is related to an impaired automatic bottom-up processing, while the top-down processing is preserved.

The present study capitalizes on the many advantages of within-subject comparisons. To that end, a group of single-sided deaf CI users was recruited. Single-sided deaf CI users have one normal hearing ear and one deaf ear implanted with a CI. This special group of CI users enabled us to investigate how cortical responses to acoustic novelty are affected by CI-transmitted input when compared to normal auditory input on a within-subject basis (Finke et al., 2016b). In ERP studies, within-subject comparisons are particularly valuable because of the usually pronounced inter-individual ERP differences (Garcia-Garcia et al., 2010a, 2010b; Gevins and Smith, 2000; Lange et al., 2015; Luck et al., 2011; Polich, 2007; Polich and Herbst, 2000; Polich and Kok, 1995; Polich and Martin, 1992; Yurgil and Golob, 2013). The elimination of inter-individual differences from the comparisons of interest contribute to the reliability of the relevant ERP measures (Baldwin et al., 2016; Clayson and Miller, 2017a, 2017b). Another advantage of the within-subjects comparison is that it is based on individuals who had ongoing auditory stimulation in one ear before their CI was implanted because they possessed a normally hearing ear. Between-subject comparisons between CI users and normal hearing listeners are confounded by the potential effects of absence of auditory stimulation that were exerted on the brains of CI users during the periods of pre-implementation deafness, such as, for example, cross-modal plasticity (Heimler et al., 2014; Sandmann et al., 2012).

The present study examined cortical responses to acoustic novelty in single-sided deaf CI users. The main interest lies in potential dissociations between early and late sub-components of the auditory Novelty-P3. Based on the available literature (see Table 1), and guided by the extended ELU model (Rönnberg et al., 2013), we expected attenuated CI-transmitted N1 and nP3E amplitudes, which reflect sensory and bottom-up attentional processing, respectively. Additionally, we expect prolonged latency for the sensory and bottom-up attentional processing. However, normal CI-transmitted nP3L and Target-P3 amplitudes and latencies, which relate to top-down attentional processing, were hypothesized.