Audiology and Neurotology

Research Article

Audiol Neurotol
DOI: 10.1159/000529485

Received: June 22, 2022
Accepted: January 31, 2023

Event-Related Potentials of Single-Sided Deaf Cochlear Implant Users: Using a Semantic Oddball Paradigm in Noise

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Keywords

Cochlear implants · Event-related potentials · Oddball · Single-sided deafness

Abstract

Introduction: In individuals with single-sided deafness (SSD), who are characterised by profound hearing loss in one ear and normal hearing in the contralateral ear, binaural input is no longer present. A cochlear implant (CI) can restore functional hearing in the profoundly deaf ear, with previous literature demonstrating improvements in speech-in-noise intelligibility with the CI. However, we currently have limited understanding of the neural processes involved (e.g., how the brain integrates the electrical signal produced by the CI with the acoustic signal produced by the normal hearing ear) and how modulation of these processes with a CI contributes to improved speech-in-noise intelligibility. Using a semantic oddball paradigm presented in the presence of background noise, this study aims to investigate how the provision of CI impacts speech-in-noise perception of SSD-CI users. ***Method:*** Task performance (reaction time, reaction time variability, target accuracy, subjective listening effort) and high density electroencephalography from twelve SSD-CI participants were recorded, while they completed a semantic acoustic oddball task. Reaction time was defined as the time taken for a participant to press the response button after stimulus onset. All participants completed the oddball task in three different free-field conditions with the speech and noise coming from different speakers. The three tasks were: (1) CI-On in background noise, (2) CI-Off in background noise, and (3) CI-On without background noise (Control). Task performance and electroencephalography data (N2N4 and P3b) were recorded for each condition. Speech in noise and sound localisation ability were also measured. ***Results:*** Reaction time was significantly different between all tasks with CI-On (*M* [*SE*] = 809 [39.9] ms) having faster RTs than CI-Off (*M* [*SE*] = 845 [39.9] ms) and Control (*M* [*SE*] = 785 [39.9] ms) being the fastest condition. The Control condition exhibited significantly shorter N2N4 and P3b area latency compared to the other two conditions. However, despite these differences noticed in RTs and area latency, we observed similar results between all three conditions for N2N4 and P3b difference area. ***Conclusion:*** The inconsistency between the behavioural and neural results suggests that EEG may not be a reliable measure of cognitive effort. This rationale is further supported by different explanations used in past studies to

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explain N2N4 and P3b effects. Future studies should look to alternative measures of auditory processing (e.g., pupillometry) to gain a deeper understanding of the underlying auditory processes that facilitate speech-in-noise intelligibility.

Introduction

Single-sided deafness (SSD) is characterised by profound hearing loss in one ear and normal hearing in the contralateral ear [Friedmann et al., 2016]. Unlike individuals with a bilateral hearing loss, SSD individuals can rely on the normal hearing ear (NHE) to understand speech in quiet, thereby reducing the impact that the hearing loss has on quality of life [Voola and Távora-Viera, 2021]. However, in noisy environments, speech intelligibility of SSD individuals decreases significantly when compared to normal hearing individuals [Van de Heyning et al., 2008; Williges et al., 2019; Körtje et al., 2022]. Speech intelligibility in noise is facilitated through the binaural squelch and binaural summation effects, both of which rely on similar inputs from both ears [Ma et al., 2016]. A cochlear implant (CI) is the only treatment option that has the potential to restore binaural hearing, thereby providing access to the advantages of bilateral hearing which in turn can improve speech understanding of SSD individuals in background noise.

A CI has the potential to restore hearing by directly stimulating the auditory nerve in the impaired ear via electrical signals. Sound transmission through the CI is degraded and does not fully encapsulate all the spectral information that the NHE provides [Drennan and Rubinstein, 2008]. Despite this limitation, a CI for SSD individuals can improve speech intelligibility in noise and localisation ability [Távora-Vieira et al., 2015, 2016; Dorbeau et al., 2018; Galvin et al., 2019; Williges et al., 2019; Wedekind et al., 2020]. These improvements highlight that the brain is capable of understanding both the acoustic signal from the NHE and the degraded electrical signal from the CI. However, it is not well understood how the underlying neural process operates to improve speech-in-noise intelligibility. One method to investigate this is by using EEG to examine event-related potentials (ERPs) evoked by the presentation of acoustic stimuli. Together, these measurements can provide an insight into the cortical processing of auditory stimuli.

Auditory ERPs have been used in the past to measure the neural processing of auditory information in CI users. ERPs are characterised by a series of deflections with a fixed time course. Scalp-distribution and amplitude differences in these deflections provide an insight into the different stages of auditory processing [Light et al., 2010]. Auditory ERPs can be elicited by an oddball paradigm which consists of frequent (standard) and non-frequent (target) stimuli, whereby participants are instructed to indicate when they hear the target stimuli. The target stimuli can differ from the standard stimuli in multiple ways, such as differences in physical properties (e.g., frequency, intensity) or semantic qualities (e.g., living vs. non-living words) [Polich, 1985; Polich et al., 1990]. However, understanding how higher order processing facilitates speech in noise understanding in SSD-CI users has yet to be investigated.

Higher order neural processing that involves discrimination and evaluation of stimuli is reflected through changes in frontocentral negativity (N2) and parietal positivity (P3b). The N2 deflection occurs within a latency range of 200–350 ms after stimulus onset, and its amplitude is enhanced upon the presentation of the target stimulus, thereby reflecting the process of discrimination [Lau et al., 2008]. As task difficulty increases in complexity, a delayed peak latency is observed which is thought to represent the difficulty in discriminating the stimuli from stored mental representation [Näätänen and Picton, 1986]. For more complex tasks, such as those involving discrimination based on semantic meaning rather than pure tone differentiation, the N2 peak latency can be delayed to around 400 ms, resulting in the peak to be labelled as the N4. This delay in peak latency is attributed to the additional time needed for individuals to fully retrieve the word's meaning from their stored mental lexicon. However, differentiating the N2 from the N4 is challenging, with many studies reporting difficulties in distinguishing the two [Deacon et al., 1991; Van den Brink et al., 2001; Finke et al., 2016]. As such, to avoid confusion and to follow in line with previous studies, the second negativity of the ERP waveform will be referred to as the N2N4 [Finke et al., 2016; Balkenhol et al., 2020].

The process of stimulus evaluation and categorisation is represented via a parietally distributed positive deflection occurring at a latency of 300–600 ms, referred to as the P3b [Polich, 2007]. The P3b is thought to represent the process of decision-making, whereby the presentation of a stimulus triggers the activation of stimulus-response links [Verleger et al., 2014]. Stimuli that are more demanding (i.e., differentiating stimuli based on meaning) have been found to elicit a P3b with smaller amplitude and delayed latency [Polich, 1985, 1986; Johnson, 1988; Verleger, 1997; Comerchero and Polich, 1999]. Additionally, past studies have identified that more involved tasks result in a larger reaction time (RT) which provides support for the decision-making hypothesis [Billings et al., 2022; Voola et al., 2022a].

Literature focussing on the higher order processing of CI users when stimulus is presented in background noise is limited. Soshi et al. [2014] investigated how the P3b is affected by noise in the CI population by presenting/ga/ and/ba/syllables. It was identified that only good performing CI users (speech perception in noise score greater than 66%) were able to elicit a P3b in noise, suggesting that the speech perception scores in CI users are positively correlated to their P3b amplitude [Soshi et al., 2014]. Finke et al. [2016] built upon the work of Soshi et al. by instructing the subjects to differentiate words as either living or non-living entities in the presence of background noise presented in the free field. Discriminating sounds based on the semantic meaning of the stimuli rather than just distinguishing based on physical properties of sound (stimulus duration or intensity) provides a firmer representation of how the higher order processes of CI users are working in everyday life. Compared to the normal hearing control, CI users exhibited delayed N2N4 and P3b latency and a delayed RT which may be attributed to the mismatch between the limited CI input and the stored mental representations.

Given the uniqueness of SSD-CI recipients, i.e., normal hearing in one ear and profound hearing loss in other ear where CI is fitted, there is a unique opportunity to isolate the impact of the CI by employing a within-subject designed experiment. Finke et al. [2016] and Wedekind et al. [2021] both identified that direct stimulation of the CI requires greater processing effort (as indicated by delayed RTs) when compared to stimulation of the NHE alone in SSD-CI users. While these studies do provide a foundation for understanding CI processing, they do not address how the electrical signal from the CI and acoustic signal from the NHE are integrated at a cortical level to provide binaural benefit. As such, in a previous study conducted by our team, we presented semantic stimuli to SSD-CI users with the aim of identifying how the higher order neural processing differs with and without the CI in free field. We found clear evidence that in free field, the brain is processing the input from both ears when the CI is on, as indicated by a significantly enhanced P2 amplitude. However, the behavioural results indicated that the addition of the CI led to greater uncertainty (larger RT variability) and delayed RT, which led us to believe that the speech in quiet task was not well set up to assess binaural hearing. This rationale is further supported by the fact that the task used did not evaluate the binaural squelch effect (an advantage of binaural hearing), thereby allowing the NHE to evaluate and discriminate the speech in quiet [Voola et al., 2023]. As such, this study was designed to build upon the findings of Voola et al. [2023] by incorporating background noise into the semantic oddball task, thereby aiming to investigate how the CI impacts speech-in-noise perception of SSD-CI users. We hypothesize that in the CI-Off condition, SSD-CI users will have poorer speech-in-noise discrimination, which will be reflected by delayed RT and smaller and delayed N2N4 and P3b effects. SSD-CI users will perform better in the CI-On condition. Using more complex variations of the oddball paradigm (i.e., in noisy environments) may provide a more thorough understanding of the underlying neural processes that facilitate higher order processing in SSD-CI users.

Materials and Methods

Participants

Twelve SSD-CI participants were recruited from the Fiona Stanley Hospital audiology department. Three participants were also part of previous study by Voola et al. [2023]. All adult participants (>18 years) had normal hearing in one ear, which was defined as having a four-frequency average (0.5, 1, 2, and 4 kHz) hearing threshold less than or equal to 20 dB HL. For patient demographics, see Table 1. In the contralateral ear, all SSD-CI participants have been using a MED-EL CI for at least 1 year. Participants gave written informed consent prior to participating in the experiment. Ethics approval was obtained from the South Metropolitan Health Ethics Committee (reference number: 335).

Sound Localisation

Sound localisation was tested using the Auditory Speech Sounds Evaluation Localisation Test. This test was conducted in a sound proof booth and presents a 4,000 Hz narrowband noise simultaneously through two loudspeakers that were placed at −60 and 60° from the participant. All stimuli were presented at 60 dB HL from one loudspeaker and, depending on the interaural level difference, presented from the other speaker at 60, 56, 40, or 30 dB. To create the illusion of a sound source localized somewhere on the azimuth between the two loudspeakers, the presentation level from both loudspeakers was adjusted to create an interaural level difference of either: −30, −20, −10, −4, 0, +4, +10, +20, +30. The software randomly picks the ILD to present at. This allowed for 13 localisation points to be established: two true speakers and 11 sham speakers. Each speaker was placed in a semicircle at 10° intervals in front of the subject, see Figure 1 [Tavora-Vieira et al., 2015].

The thirteen loudspeakers were numbered from −6 to 6 with the two real loudspeakers designated as −6 and 6. The participant was required to report which of the thirteen speakers was perceived to be the source. After each response made by the participant, their

Table 1. Demographic information of participants age, gender, duration of deafness, cause of deafness, side of implant, pure tone average (PTA), inserted electrode type, and experience with the CI

Participant	Age, years	Gender	Duration of deafness, years	Aetiology	CI ear	CI ear PTA threshold, dB HL	NHE PTA threshold, dB HL	Type of electrode	CI experience, years
1	60	F	41	Mumps	L	NR	11	FLEX28	13
2	57	F	0.9	ISSNHL	L	NR	19	FLEX28	9
3	65	F	12	ISSNHL	L	86	8	FLEX28	3
4	69	F	20	Electric shock	L	82	17	FLEX28	3
5	70	F	2	Stroke	R	72	11	FLEX28	1
6	69	F	0.6	MD	L	73	20	FLEX28	9
7	54	F	0.6	ISSNHL	L	116	20	FLEX28	4
8	50	M	12	Head trauma	L	76	5	FLEX28	9
9	69	F	0.5	ISSNHL	R	79	20	FLEX28	2
10	56	M	30	ISSNHL	L	NR	10	FLEX28	6
11	53	M	8	ISSNHL	L	85	3	FLEX28	3
12	65	F	40	ISSNHL	L	80	12	FLEXSOFT	10

ISSNHL, idiopathic sudden sensorineural hearing loss; MD, Meniere's disease.

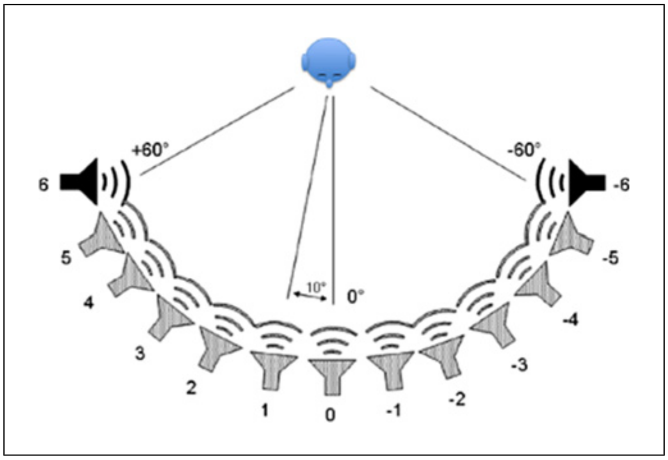

Fig. 1. Set-up of the localisation test. The participant was seated facing speaker number 0. The black speakers 6 and −6 are the two true speakers and the grey speakers (−5 to 5) are the sham speakers. Each speaker is positioned 10° apart.

answer was inputted into the computer software which calculated the median values and root mean square. A lower root mean square indicated better localisation ability.

The total test consisted of 33 items. All narrowband noise presentation locations were randomly selected by a computer software. Stimuli with intensity differences of −30, −20, −10, 10, 20, and 30 dB were presented three times each, and stimuli with intensity differences of −4, 0, and 4 dB were presented five times each.

Speech Perception in Noise

The Bamford-Kowal-Bench adaptive speech-in-noise test was used to measure the speech-in-noise intelligibility of the SSD-CI participants [Bench et al., 1979]. Each participant underwent the assessment under three different spatial configurations: S0/N0 (speech and noise presented from the front), S_{CI}/N_{NHE} (speech presented to the side of the CI and noise presented to the side of the NHE), and S_0/N_{NHE} (speech presented from the front and noise to the NHE). All configurations were tested twice, with and without the CI, and block orders were counterbalanced across participants [Távora-Vieira et al., 2015, 2016; Wedekind et al., 2018, 2020, 2021].

Behavioural Data

We examined task performance by measuring RT, RT variability (standard deviation of RTs within each condition), and target accuracy. RT was defined as the duration between target stimulus onset and the pressing of the response button. RT was calculated at a trial level and then averaged across trials to get the grand mean. RTs exceeding than 1,500 ms were excluded from further analysis. Reaction time variability was calculated by averaging the standard deviation of the participant's reaction times for each task at a trial level. Target accuracy was calculated as the proportion of correct responses out of a total of 48 target stimuli presented per condition.

Subjective Listening Effort

Subjective listening effort was also measured after the completion of each condition. Participants verbally indicated their subjective listening effort according to a seven-point scale, where 1 indicated "No Effort" and 7 indicated "Extreme Effort" [Luts et al., 2010; Holube et al., 2016].

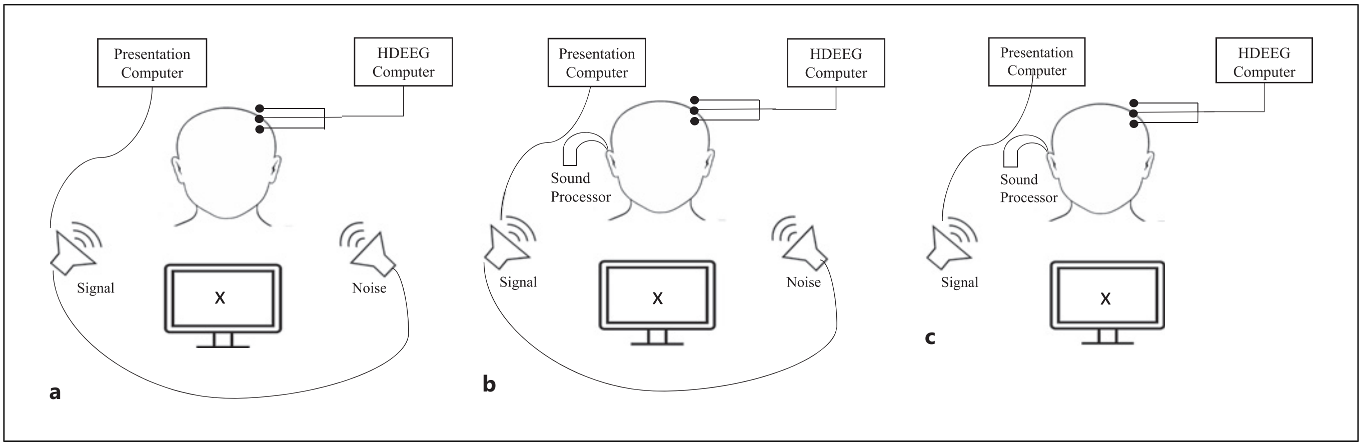

Fig. 2. Schematic diagram illustrating the set-up of the three experimental conditions. CI-Off (**a**), CI-On (**b**), and Control (**c**).

Oddball Task

This study used a semantic oddball paradigm consisting of odd and even numbers from one to nine that was presented in the presence of background noise [Voola et al., 2022a]. The semantic oddball task was presented in three different conditions: (1) CI-Off – semantic oddball task and noise with the CI-Off, (2) CI-On – semantic oddball task and noise with the CI-On, and (3) Control – semantic oddball tasks presented with the CI-On (no noise). Eight-talker background noise wave files were attained from the National Acoustic Laboratories. Speech and noise were presented in free field from two different speakers at 45° azimuth from the subject – with the signal (odd and even numbers) always being presented to the CI side. In all conditions, participants were instructed to look at a fixation cross presented on a computer monitor at one metre. This was implemented to reduce eye movement. See Figure 2 for a schematic diagram of the experimental set-up for the three conditions.

The odd/even oddball paradigm was presented pseudorandomly such that a target stimulus was presented with a probability of 20% (48 presentations) and a standard stimulus was presented with a probability of 80% (196 presentations). Each stimulus was presented with an interstimulus interval of 1,500 ms. In addition, the task order was counterbalanced across participants. The task consisted of odd numbers from one to nine (one, three, five, nine) and even numbers (two, four, six, eight). The number seven was omitted from the odd list as it contains two syllables. These speech files were recorded with the purpose of being used in a telephone-based speech-in-noise test called "Telescreen" [Dillon et al., 2016]. Each recorded number was modified using the software "Audacity®" [Audacity, 1999–2016] so that each number was of an approximate duration of 400 ms. Speech babble was presented at 55 dB HL and the numbers were presented at 60 dB HL – resulting in a signal-to-noise ratio of +5 dB HL.

Acquisition and Pre-Processing of Electrophysiological Data

Electrophysiology data were continuously recorded for the duration of each condition of the oddball task. The data were acquired using the Micromed™ SD LTM EXPRESS system with Gilat Medical ERP software (Gilat Medical Research and Equipment Ltd., Karkur, Israel). A sampling rate of 1,024 Hz with an online low-pass filter of 40 Hz was used to digitise the data. Data were recorded using Ag/AgCl electrode cap (SpesMedica™ Genova, Italy). The Ag/AgCl electrode cap consisted of 59 electrodes, which were arranged in accordance with the 10–20 system. An additional four electrodes were used to: (1) account for myogenic artefact arising due to eyeblinks from an electrode placed under the infraorbital region of the right eye, (2) an electrode placed on the lateral temporal orbital region of the right eye to account for myogenic artefact arising from lateral eye movement, (3) a reference electrode that was placed on the middle of the chin, and (4) a ground electrode placed on the right mastoid. All electrode impedance was kept below 5 kΩ for the duration of the recording.

MATLAB 2020a was used to process the data. A semi-automated procedure was used consisting of functions from the plug-ins EEGLAB [Delorme and Makeig, 2004], PREP pipeline [Bigdely-Shamlo et al., 2015], clean_rawdata() plugin, AMICA [Palmer et al., 2011], and ICLabel plugin [Pion-Tonachini et al., 2019]. The removeTrend() from the PREP pipeline plugin was used to linearly detrend the data using a high-pass 1 Hz FIR filter with a 0.02 step size. The cleanLineNoise() from PREP pipeline plugin was used to remove 50 Hz line noise and harmonics up to 500 Hz. The pop_clean_rawdata() was used to determine noisy channels. The pop_interp was used to interpolate noisy channels spherically. EEG data were then downsampled to 250 Hz. The data were demeaned, and a 30 Hz low pass filter was applied using the pop_eegfiltnew() with a filter order of 100. The clean_asr() was used to correct for artefacts using the artefact subspace reconstruction method. Data were then epoched from –200–1,000 ms relative to stimulus onset. Independent component analysis of the data was conducted using AMICA (2,000 iterations) on downsampled data to 100 Hz [Palmer et al., 2011]. The number of independent components extracted was adjusted for the data rank. The baseline data were correct to the pre-stimulus interval (–200 to 0 ms). Trials with activity exceeding 100 mV were flagged for exclusion for further analysis. SASICA was used to guide the manual rejection of ICA components that were deemed to be too noisy (mean = 22 components removed).

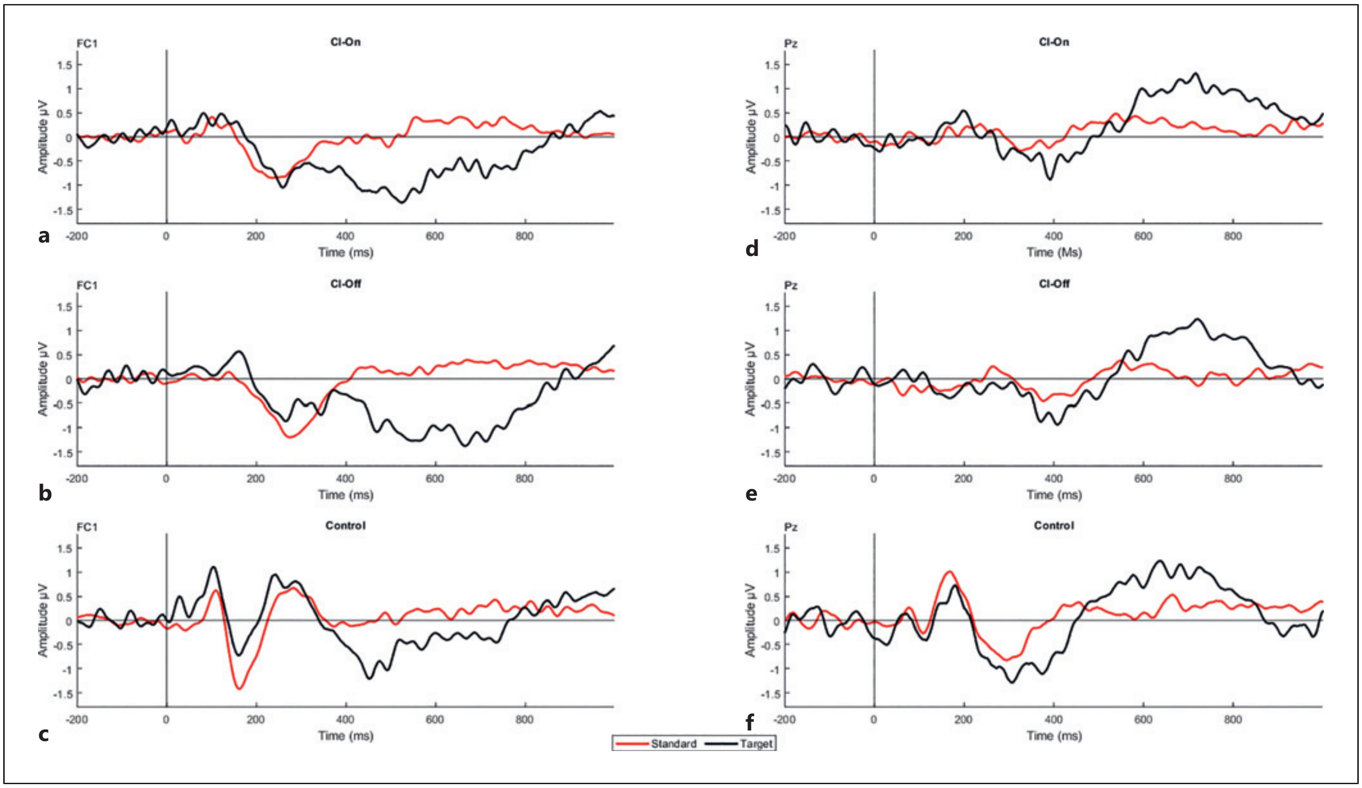

Fig. 3. Grand mean ERP waveforms for each stimulus (Standard, Target) and presentation conditions (CI-On, CI-Off, Control). Panels **a**, **b**, and **c** depict grand mean waveforms recorded from frontocentral electrode FC1 and panels **d**, **e**, and **f** depict grand mean waveforms recorded from parietally distributed electrode Pz.

Measurement of ERPs

We measured amplitude of N2N4 and P3b ERP components by calculating the area of standard-target effects on "target-minus-standard" ERP difference waveforms (Fig. 3). These measurements were conducted at the trial level by subtracting the individual averaged standard ERP of each condition from each individual target trial of the corresponding condition. We measured N2N4 at FCz and P3b at Pz, corresponding to the site where the size of standard-target N2N4 and P3b effects were most prominent. Given the temporally distributed nature of each different ERP, we used broad time windows (300–800 ms for N2N4 and 500–950 ms for P3b) to capture each component and excluded positive areas for N2N4 and negative areas for P3b. The same time windows were used for all three hearing conditions. The latency of the N2N4 and P3b were estimated using the 50% area latency method.

Statistical Analysis

All statistical analyses were conducted using R statistics and R Studio software [RStudio, 2020]. We conducted linear mixed model analysis using the "lme" function from the "nlme" package [Pinheiro et al., 2022]. For localisation, speech in noise, RT, subjective listening effort and target accuracy, we included condition (CI-Off, CI-On, and Control) as a fixed effect, and intercepts for participants were modelled as a random effect. For electrophysiological measures (N2N4, P3b), we also included trial-type as an additional fixed effect, interacting with the effect of the ear.

Results were analysed using the "ANOVA" function and presented as F-values. Follow-up pairwise comparisons were conducted using the "emmeans" and "contrast" functions from the "emmeans" package [Lenth et al., 2020]. Pairwise results were presented as t-ratios (mean difference estimates divided by standard error), and *p* values for multiple comparisons were corrected using the "Holm" method. The function "emmeans" was also used to plot values and error bars for figures presented in the results.

Results

Localisation and Speech in Noise

For localisation, the linear mixed model analysis revealed a significant effect of CI ($F(1,49) = 102.79$, $p < 0.0001$*), indicating an improvement in sound localisation ability with the CI-On compared to CI-Off (*M* [*SD*] = 23.6 [11.1] versus 50.0 [18.0] degrees; *Est. Mean Diff.* [*SE*] = 26.4 [2.6] degrees) (Fig. 4a). Note that an asterisk (*) indicates a significant difference.

For speech in noise, the linear mixed model analysis revealed significant main effects of CI ($F(1,45) = 22.74$, $p < 0.0001$*) and sound presentation ($F(2,45) = 90.94$, $p <$

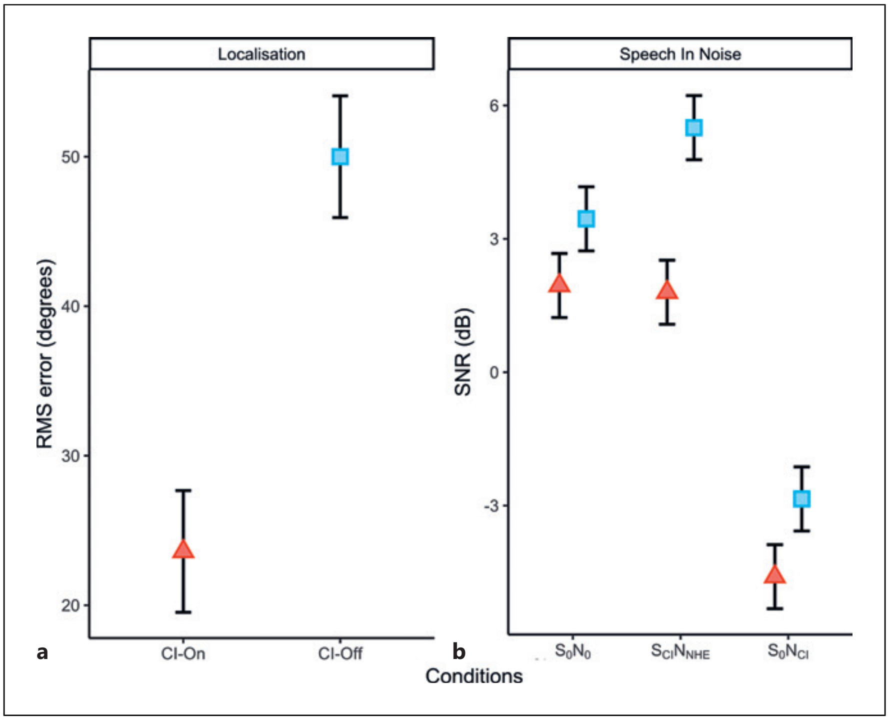

Fig. 4. a Group means with within-subject standard error bars for speech-in-noise intelligibility using the Bamford-Kowal-Bench speech-in-noise test. Test was conducted in three spatial configurations, with and without the CI; S0N0 – speech and noise from front, Sci/Nhe – speech from CI side, noise from NHE side and S0/Nci – speech from front, noise from CI side. **b** Sound localisation test results with and without the CI. A lower RMS indicates better sound localisation ability. RMS, root mean square.

0.0001*), but the two-way interaction was not statistically significant ($F(2,45) = 2.05$, $p = 0.141$). Pairwise contrasts between CI-On and CI-Off for each configuration revealed that there was a significant improvement with $S_{CI}N_{NHE}$ (t-ratio [45] = 4.40, $p = 0.0002$*, *Est. mean diff.* [*SE*] = 3.70 [0.84]) but not in S_0N_0 (t-ratio [45] = 2.08, $p =$ 0.087, *Est. mean diff.* [*SE*] = 1.75 [0.84]) or S_0N_{CI} conditions (t-ratio [45] = 1.78, $p = 0.087$, *Est. mean diff.* [*SE*] = 1.50 [0.84]) (Fig. 4b).

Reaction Time, Target Accuracy, and Subjective Effort

For reaction time, the linear mixed model analysis revealed a significant effect of task condition ($F(2,1624) =$ 29.34, $p < 0.0001$*). RTs were shortest in Control condition (no-noise with CI-On, M [SD] = 784 [143] ms) followed by CI-On (807 [126] ms) then CI-Off with noise (850 [161] ms) (Fig. 5a). Differences in RT between task conditions were all statistically significant (Control vs. CI-On: t-ratio [1,624] = 3.08, $p = 0.0021$*, *Est. mean diff.* [*SE*] = 24.4 [7.9] ms; Control versus CI-Off: t-ratio [1,624] = −7.62, $p < 0.0001$*, *Est. mean diff.* [*SE*] = 60.6 [7.95] ms, CI-On versus CI-Off: t-ratio [1,624] = 4.54, $p <$ 0.0001*, *Est. mean diff.* [*SE*] = 36.2 [7.97] ms).

Target accuracy (Fig. 5b) exceeded 90% on all task conditions, with the lowest means for CI-Off and the highest means for Control (Control: M [SD] = 96.18 [8.42]%; CI-On: 95.14 [9.91]%; CI-Off: 93.06 [12.60]%). However, the linear mixed model analysis indicated that differences in accuracy between task conditions were not statistically significant ($F(2,22) =$ 2.66, $p = 0.0927$).

Subjective listening effort (Fig. 5c) measured after the completion of each condition revealed that participants perceived the CI-Off condition as requiring the greatest listening effort, followed by CI-On and then Control condition (Control: M [SD] = 1.08 [1.38], CI-On = 2.08 [1.62], CI-Off = 3.42 [1.08]). The linear mixed model analysis revealed a statistically significant effect of task condition ($F(2,22) = 22.93$, $p < 0.0001$*). Follow-up pairwise comparisons showed that differences in subjective effort ratings between all task conditions were statistically significant (Control vs. CI-On: t-ratio [22] = 2.89, $p = 0.0221$*, *Est. mean diff.* [*SE*] = 1 [0.25]; Control versus CI-Off: t-ratio [22] = 6.75, $p < 0.0001$*, *Est. mean diff.* [*SE*] = 2.33 [0.25]; t-ratio [22] = 3.86, $p = 0.0024$*, *Est. mean diff.* [*SE*] = 1.33 [0.35]).

N2N4 Area Amplitude and 50% Area Latency

N2N4 area amplitude was calculated using different waveforms recorded from a frontocentral electrode (Fig. 6). The linear mixed model analysis showed that there was no statistically significant difference in area amplitude between task conditions ($F(2,1614) = 1.24$, $p =$ 0.289). However, there was a significant main effect of

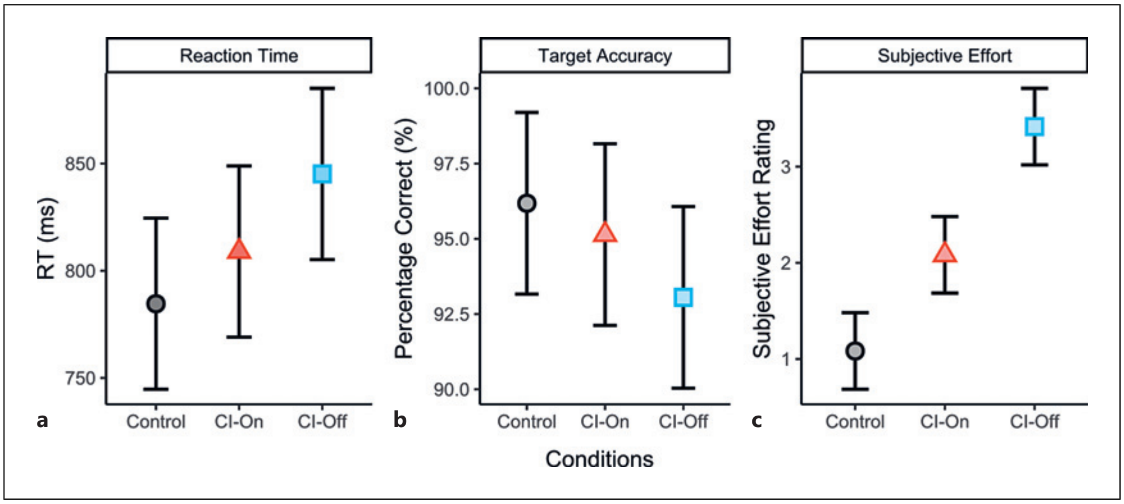

Fig. 5. Grand mean estimates with error bars depicting the standard error of the mean. Reaction time (**a**), target accuracy **(b)**, and subjective listening effort **(c)**.

task condition on latency (*F*(2,1624) = 5.4, *p* = 0.0045*). As depicted in Figure 4, mean latency was shortest for Control (M [SD] = 520 [33] ms), followed by CI-On (535 [26] ms) and CI-Off (552 [42] ms). Follow-up pairwise comparisons revealed that differences in area latency between Control and CI-Off were statistically significant (*t*-ratio [1,624] = 3.28, *p* = 0.0032*, *Est. mean diff.* [*SE*] = 32.8 [10] ms) but not for Control versus CI-On (*t*-ratio [1,624] = 1.36, *p* = 0.175, *Est. mean diff.* [*SE*] = 13.5 [9.94] ms) and CI-On versus CI-Off (*t*-ratio [1,624] = 1.93, *p* = 0.1079, *Est. mean diff.* [*SE*] = 19.3 [10.03] ms).

P3b Area Amplitude and 50% Area Latency

Difference waveforms (target minus standard) were used to calculate the P3b area using a parietal electrode (Fig. 7). Linear mixed model analysis revealed a significant main effect of task condition (*F*(2,1612) = 4.34, *p* = 0.0132*). Follow-up pairwise comparisons showed that P3b area amplitude was significantly greater for Control compared to CI-On (*t*-ratio [1,612] = 2.43, *p* = 0.0305*, *Est. mean diff.* [*SE*] = 21.30 [8.77] μV*ms) and CI-Off (*t*-ratio [1,612] = 2.65, *p* = 0.0242*, *Est. mean diff.* [*SE*] = 23.39 [8.82] μV*ms) but not between CI-On versus CI-Off (*t*-ratio [1,612] = 0.24, *p* = 0.8127, *Est. mean diff.* [*SE*] = 2.09 [8.84] μV*ms).

Looking at P3b 50% area latency, the main effect of task condition was approaching statistical significance (*F*(2,1612) = 2.90, *p* = 0.056). Follow-up pairwise comparisons, revealed P3b area latency was significantly shorter for Control compared to CI-On (*t*-ratio [1,612] = 2.41, *p* = 0.048*, *Est. mean diff.* [SE] = 25.5 [10.6] ms), but differences between Control versus CI-Off (*t*-ratio [1,612] = 1.15, *p* = 0.249, *Est. mean diff.* [*SE*] = 12.3 [10.6] ms), and CI-On versus CI-Off (*t*-ratio [1,612] = 1.24, *p* = 0.249, *Est. mean diff.* [*SE*] = 13.2 [10.7] ms) were not statistically significant.

Discussion

In the present study, we examined the neural processing of words presented with background noise in SSD-CI users. In particular, we focused on understanding how the CI impacts the ability to discriminate odd/even numbers by comparing ERP results obtained with and without the CI and assessed the effect of noise by contrasting the results with a no-noise (Control) condition. We also characterised functional hearing ability by measuring sound localisation and speech-in-noise intelligibility with and without the CI. In the functional hearing task, we identified a significant improvement in both tests when the CI was switched on. In the semantic oddball task, the best performance was observed during the no-noise condition, but under noisy conditions, participants performed better during CI-On compared to CI-Off, as indicated by faster RT, higher target accuracy, and a lower subjective listening effort rating. For ERPs, we observed an effect of condition on N2N4 latency (Control < CI-On < CI-Off) and P3b amplitude (Control > CI-On/Off) and latency (Control < CI-On/Off). Overall, the behavioural results obtained from this study show partial support for our initial hypothesis that performance with

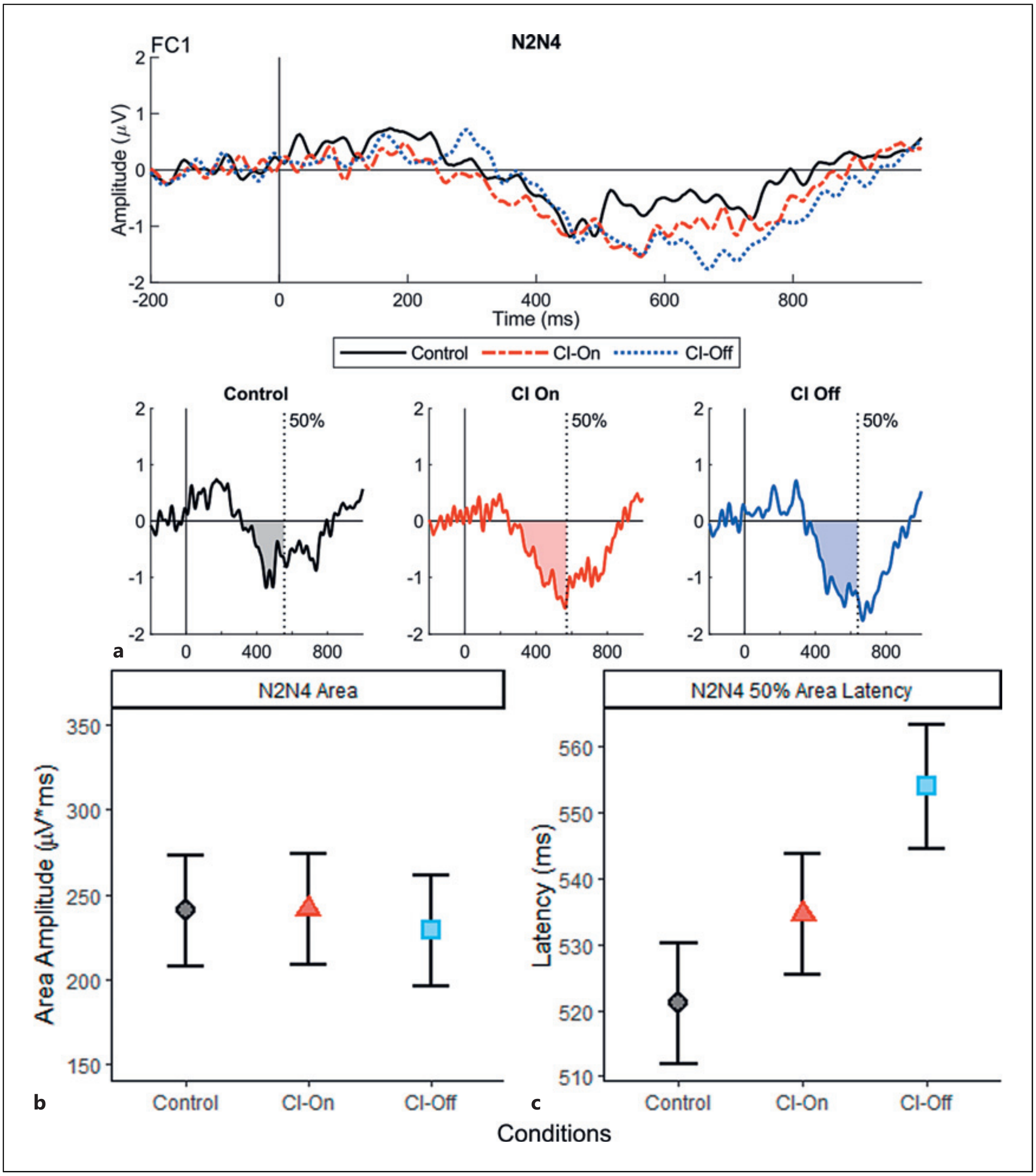

Fig. 6. ERPs measured from a frontocentral electrode (FCz). **a** Waveform difference (target minus standard) for all three testing conditions. The grey highlighted region indicates the time window used to measure the N2N4 (300–800 ms). **b**, **c** Mean area and latency reflecting the N2N4 measured in all three conditions, respectively.

the CI-On will be better than with the CI-Off in terms of RT, target accuracy and perceived subjective listening effort. However, these behavioural results did not translate into corresponding reductions in latency or increases in amplitude of ERP waveforms that we initially hypothesized.

Functional Hearing: Speech in Noise and Sound Localisation

Functional improvement with CI was observed during the speech-in-noise test. The improvement was most prominent when the speech signal was directed at the CI side ($S_{CI}N_{NHE}$). Smaller CI-related improvements were

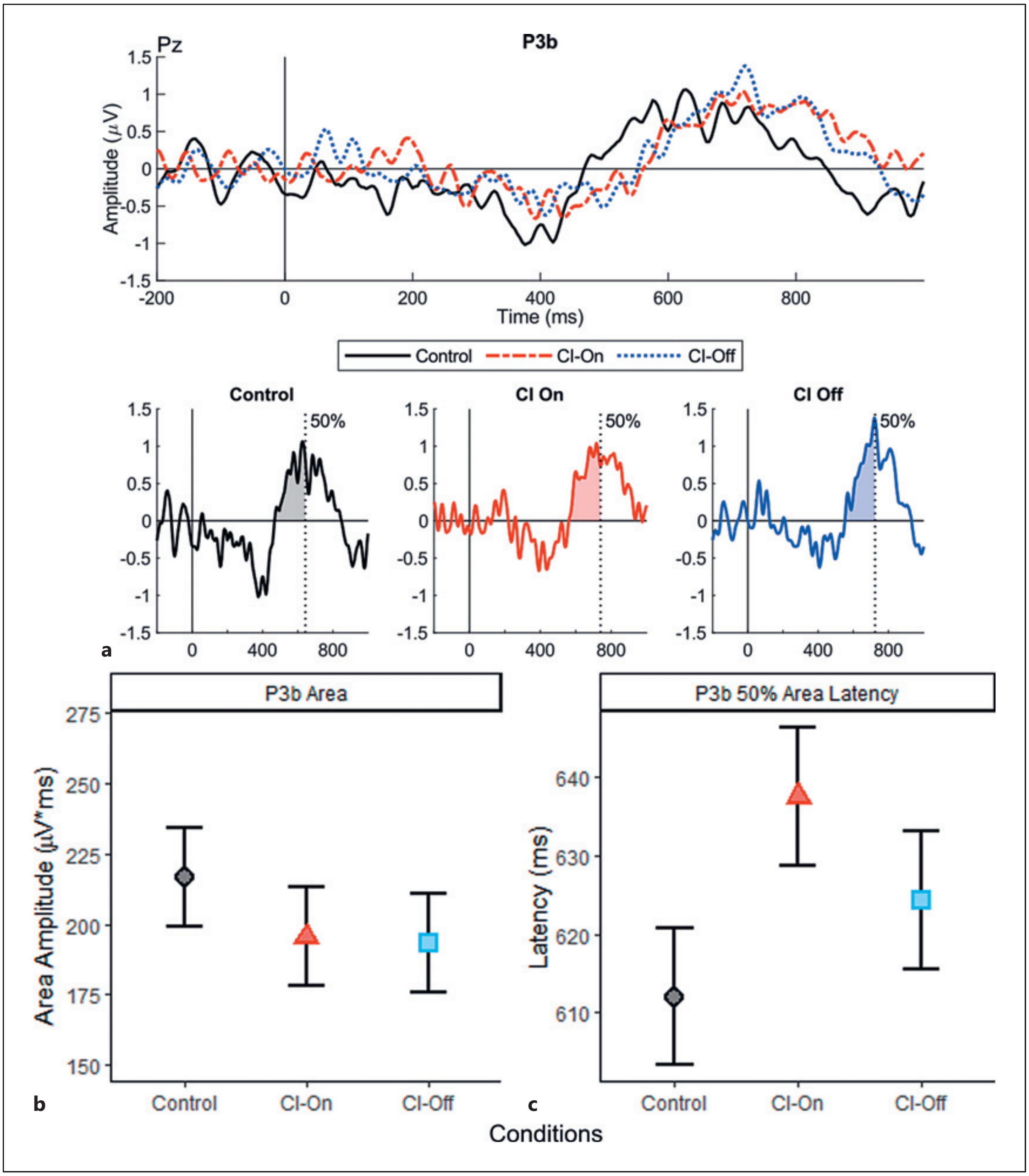

Fig. 7. ERPs measured from a posterior electrode (Pz). **a** Waveform difference (target minus standard) for all three testing conditions. The grey highlighted region indicates the time window used to measure the P3b (500–950 ms). **b**, **c** Mean area and latency reflecting the P3b measured in all three conditions, respectively [Voola et al., 2022b].

also observed in S_0N_0 and S_0N_{CI} configurations; however, these did not reach the threshold for statistical significance ($p = 0.87$). While it may have been expected to see an improvement in speech in noise with the CI-On, this lack of improvement could be attributed to the participants in the study having a wide variation in CI listening experience ranging from 1 to 13 years, and six of whom had less than 5 years of listening experience. Previous studies have identified that speech-in-noise performance can significantly increase after 5 years of CI experience [Dillon et al., 2013]. Nevertheless, these smaller effects highlight the dominance of the NHE in S_0N_0 [Van de

Heyning et al., 2008; Arndt et al., 2011; Dorbeau et al., 2018] and that the CI is not detrimental to speech intelligibility when noise is coming from the CI side [Wedekind et al., 2021]. Likewise, a statistically significant improvement in sound localisation was seen with the CI-On, consistent with previous studies [Vermeire and Van de Heyning, 2009; Firszt et al., 2012; Távora-Vieira et al., 2015; Wedekind et al., 2021]. Collectively, these results demonstrate that the CI is capable of restoring binaural hearing in SSD patients.

Semantic Oddball Task: Task Performance

In line with the functional hearing results, RTs to target stimuli in the Oddball task were significantly faster during CI-On compared to CI-Off, indicating that the additional signal from the CI facilitates the ability to process and identify target words. RT in the Control condition (no noise with CI) was significantly shorter than both CI-On and CI-Off. This performance increase was also accompanied by the reporting of lower subjective listening effort with CI-On compared to CI-Off, demonstrating that the use of CI reduce percieved task difficulty. Similarly, subjective effort ratings to the control condition were significantly lower than CI-On and CI-Off. Although RT was slowest and the task was perceived as the most effortful during CI-Off, participants were highly accurate across all conditions (<90%). While the main effect of condition was not statistically significant, inspection of mean values indicated that CI-Off was lowest (93%), followed by CI-On (95.1%) and Control (96.2%), which is in line with the subjective effort ratings.

Collectively, these behavioural results demonstrated that (1) the use of background noise had a significant impact on objective performance as well as subjective perceptions of task difficulty – but participants were able to successfully complete the task despite the noise – and (2) that use of background noise allowed us to show a measurable improvement in bilateral hearing (CI-On) compared to hearing with the NHE alone (CI-Off).

Semantic Oddball Task: Neural Responses

With respect to neural processing, we identified that with the CI-Off, N2N4 latency was significantly increased compared to the Control condition. This is consistent with previous within-group observations, such as by Almeqbel and McMahon [2015] who examined neural responses to speech-tokens in background noise using a passive task with young children. They reported delayed N2N4 latencies in with lower (−10 dB) compared to higher SNR conditions (+20 dB). Our results are also consistent with Finke et al. [2016], who reported delayed N2N4 latencies in CI users compared to a normal hearing control group. One interpretation for the delay is that it reflects the increased effort in accessing lexical information during adverse listening conditions [Finke et al., 2016]. Alternatively, the delay could also reflect increased effort needed to resolve lower level uncertainty in the sound signal, whereby previous studies have attributed this uncertainty to the CI [Obleser et al., 2007; Cope et al., 2017], but in our study, we attribute this uncertainty to the background noise. Although our task required word discrimination and our N2N4 results could be interpreted in the context of retrieving word meanings from the mental lexicon, we cannot rule out the possibility that our results may be driven by more general lower level uncertainties. Nevertheless, our N2N4 findings suggest that the higher order cognitive processes involved in evaluating the simple words requires more time under noisy conditions, without the CI.

With respect to P3b area latency, we observed that the Control condition had a significantly shorter latency when compared with the CI-On. However, the difference between CI-Off and CI-On/Control was not statistically significant. With respect to amplitude, a similar pattern was observed, where P3b amplitudes were more positive during control compared to CI-On, but no differences were observed between CI-On and CI-Off.

Focussing on P3b area latency, we observed that the no-noise Control condition had a significantly shorter latency compared with noise conditions (CI-On and CI-Off) [Polich, 2007]. Additionally, we identified significantly shorter RT and lower perceived subjective listening effort results for the Control condition. Taken together, the P3b area latency and behavioural results indicate that SSD-CI users are able to discriminate and evaluate auditory stimuli quicker in the absence of noise. Despite the lack of statistically significant differences in P3b area between CI conditions, we did identify that the P3b area was largest in the control condition which was likely to be the easiest condition, as indicated by smallest RT and subjective listening scores. The larger P3b area for the Control condition suggests that in the absence of noise, evaluation of auditory stimuli is easier when compared to situations in noisy environments [Polich, 2007].

The P3b area and latency findings are surprising, given that functional assessments indicated that SSD listeners demonstrate improvements in speech-in-noise intelligibility with a CI. We would have expected this improvement in functional assessment, along with the behavioural results (RT and subjective listening effort), to result in correspondingly larger P3b areas and earlier latency being recorded for CI-On when compared with CI-Off, but this was not observed. These findings allude to the possibility that EEG may not be sensitive enough to detect within-subject differences. The clear differences observed in the behavioural data and the lack of differences in the EEG data suggest that there are limitations with using EEG as a measure of cognitive processing.

Reliability of ERPs as Measures of Cognitive Processing

The lack of consistency in the explanation of N2N4/P3b responses in the present and previous studies highlights that using N2N4/P3b to measure cognitive effort may be more complex and subject to large degrees of variability. Finke et al. identified that the N2N4 amplitude was greater upon direct stimulation of the CI compared to that seen when the NHE was stimulated. This was attributed to lexical processing. This larger N2N4 reflected greater effort to match the sound with the mental lexicon, showing support for the conflict monitoring hypothesis [Finke et al., 2016]. Conversely, in previous work conducted by our lab, we identified that a smaller N2N4 was recorded from directly stimulating the CI in comparison to the NHE [Wedekind et al., 2021; Voola et al., 2023]. Wedekind et al. [2021], using an auditory oddball paradigm consisting of pure tones (1 kHz and 2 kHz), found that compared to the NHE, the CI showed a smaller N2, but the P3b was similar between the NHE and CI. However, given the simplicity of the pure tone oddball task, it is likely that this task reflects only early discrimination process as represented by the N2, as deeper evaluation of stimulus was not needed [Wedekind et al., 2021].

To build on the findings of Wedekind et al. [2021], our lab conducted a follow-up study whereby SSD-CI users had to discriminate between odd and even numbers, comparing both the NHE versus CI (both via direct stimulation) and also in free field, with and without the CI. We identified that N2N4 and P3b were both similar between the NHE and CI, even though the behavioural data indicated that evaluation of auditory stimuli from the CI was significantly slower in RT when compared to the NHE. For free field, we observed similar N2N4, P3b, and RT results between CI-On and CI-Off, which suggested that the NHE was dominating the response. This rationale was developed due to the stimuli used in the study not containing any binaural cues. As such, the current study was implemented for noise using an auditory oddball tasks.

The current and previous studies [Finke et al., 2017] have implemented a more complex task in order to reveal a deeper insight into the higher order processes of SSD-CI users. Finke et al. compared CI users with normal hearing controls, evaluating their higher order processing of speech using German two-syllable words in noise. Overall, the current study and Finke et al. identified that SSD-CI participants performed better behaviourally (shorter RTs) without noise than with noise. However, in both studies, the N2N4 and P3b recordings showed mixed results. Finke et al. [2017] observed that in the most complex task (modulated noise), P3b area was larger when compared to the no-noise condition. Conversely, in the current study, we observed that the most complex condition (CI-Off) elicited the smallest P3b area. These inconsistencies in EEG data between studies highlight the large variability with using N2N4 and P3b to measure cognitive ability. Additionally, implementing noise into an auditory oddball task may not be the answer to be able to gain a deeper understanding of cognitive ability of SSD-CI users. This is highlighted by the fact that early ERPs (N1-P2), which are thought to have downstream effects on later ERPs (N2N4 & P3b), cannot be identified in the waveforms generated from noisy conditions but can be seen in the no-noise condition (Fig. 3). The absence of clear early ERPs highlights that the adding more noise to the auditory oddball paradigm will only result in the waveforms generated being more difficult both to interpret and to compare with previous studies in which no noise was used. To overcome these issues with N2N4 and P3b measurements, future studies should look to employ alternative measures such as pupillometry which has been shown in past literature to be a good measure of cognitive effort [Piquado et al., 2010; López-Ornat et al., 2018].

Conclusion

In the present study, we identified significant differences in RT and subjective listening effort, both indicating that the Control condition was both objectively and subjectively the easiest condition. Despite significant differences in RT, the neural responses (N2N4 and P3b) did not follow the same trend for all three conditions. The lack of consistency between the behavioural and neural responses highlights the variability in using N2N4 and P3b to measure cognitive effort. This was emphasised by previous studies employing different explanations for N2N4 and P3b effects. This highlights the need for caution to be taken when designing auditory oddball tasks with CI patients in future studies. By using other forms of measures for cognitive ability (such as pupillometry) in speech-in-noise task with SSD-CI users, this knowledge could potentially guide implantation candidacy guidelines and management rehabilitation protocols.

Acknowledgments

National Acoustics Laboratories provided the eight-talker speech babble. Patrick Connolly helped with English clarity and accuracy on a version of this manuscript.

Statement of Ethics

Ethics approval was obtained from the South Metropolitan Health Ethics Committee (reference number: 335). Participants have given their written informed consent to participate in this study.

Conflict of Interest Statement

The authors report no competing interests.

Funding Sources

This research was partially supported by the Australian Government through the Australian Research Council's Discovery Projects funding scheme (project DP180100394) awarded to WM. This project did not receive any other specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

DT awarded the research fellowship grant from the Rayne Medical Research Foundation. https://www.rainefoundation.org.au/research/funding-opportunities/clinician-research-fellowships/. The funders did not play any role in the study design, data collection, analysis, preparation of the manuscript, or decision to publish.

Author Contributions

Marcus Voola: drafting, design, data collection, interpretation, and final approval. Andre Wedekind: drafting, design, and interpretation. An T. Nguyen: drafting, design, analysis, and interpretation. Welber Marinovic: drafting, final approval, and interpretation. Gunesh Rajan: interpretation, drafting, and final approval. Dayse Tavora-Vieira: interpretation, drafting, final approval, and design.

Data Availability Statement

All data generated or analysed during this study are included in this article. Further enquiries can be directed to the corresponding author. "A preprint version of this article is available on medRxiv "2022.06.30.498355". This preprint was last edited on July 3, 2022. Voola M, Wedekind A, Nguyen AT, Marinovic W, Rajan G, Tavora-Vieira D. Event-Related Potentials of Single Sided Deaf Cochlear Implant Users – Using a Semantic Oddball Paradigm in Noise. BioRxiv498355 [Preprint]. January 27, 2023

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