# Effects of Stimulus Duration on Event-Related Potentials Recorded From Cochlear-Implant Users

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**Objectives:** Several studies have investigated the feasibility of using electrophysiology as an objective tool to efficiently map cochlear implants. A pervasive problem when measuring event-related potentials is the need to remove the direct-current (DC) artifact produced by the cochlear implant. Here, we describe how DC artifact removal can corrupt the response waveform and how the appropriate choice of stimulus duration may minimize this corruption.

**Design:** Event-related potentials were recorded to a synthesized vowel /a/ with a 170- or 400-ms duration.

**Results:** The P2 response, which occurs between 150 and 250 ms, was corrupted by the DC artifact removal algorithm for a 170-ms stimulus duration but was relatively uncorrupted for a 400-ms stimulus duration.

**Conclusions:** To avoid response waveform corruption from DC artifact removal, one should choose a stimulus duration such that the offset of the stimulus does not temporally coincide with the specific peak of interest. While our data have been analyzed with only one specific algorithm, we argue that the length of the stimulus may be a critical factor for any DC artifact removal algorithm.

**Key words:** Cochlear implant, EEG, Artifact removal.

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## INTRODUCTION

Cochlear implants (CIs) can be highly effective at restoring speech understanding to individuals with severe-to-profound hearing loss. Some individuals can score above 80% in speech perception tasks administered in quiet (Gifford et al. 2008), but such positive results are not realized in every CI user. This variability in performance is a result of multiple factors, including those that are biological, surgical, or device-related in nature. Device-related factors include the proper programming of the device, which needs to be tailored to each individual user. Proper programming that maximizes speech understanding is performed by an audiologist; this includes determining the frequency-to-electrode allocations, stimulation rates, and stimulation levels. Proper CI programming often involves behavioral responses, such as reporting comfortable stimulation levels. However, not everyone can participate in behavioral testing (e.g., infants), and behavioral measures may fail to yield the parameters that would result in maximum speech understanding.

As an alternative to behavioral measures, CI program parameters may be optimized with electrophysiological (EEG) objective measurements (Gilley et al. 2006; Friesen & Picton 2010; Viola et al. 2012; Lopez Valdes et al. 2014; Scheperle & Abbas 2015; Gordon et al. 2016). Another advantage of using an objective measure like EEG is that it has the potential for increasing the efficiency of the CI programming process, thus addressing the time constraints currently imposed upon CI audiologists. The event-related potentials (ERPs) P1, N1, and P2 (which normally occur at around 50, 100, and 200 ms, respectively) have been investigated in CI users (Ponton et al. 1996; Friesen et al. 2009) and are well suited for consideration in the programming process because their latency and amplitude are known to be modulated both by the physical features of the acoustical stimulus, as well as by attention and age (Tremblay et al. 2003; Wunderlich et al. 2006).

Despite the promise of using EEG to optimize CI programming, barriers do exist. A main problem related to collecting EEG recordings from CI users is the presence of substantial recording artifacts, which originate primarily from two sources. The first source arises from the radio-frequency transmission generated by the transmitter and receiver that pass information from the external sound processor to the internal device (Hofmann and Wouters 2010; Friesen & Picton, 2010). The second source arises from the electrical pulses delivered by intracochlear electrodes of the internal device. Several algorithms have been used to remove these recording artifacts, including independent component analysis (Viola et al. 2012; Sandmann et al. 2015) and multivariate regression analysis (Mc Laughlin et al. 2013). Here, we show that the artifact removal algorithm adopted by Mc Laughlin et al. can be affected by parameters related to the stimulus. Specifically, our results suggest that the duration of the stimulus should be carefully considered to avoid corruption of ERP peaks of interest. More generally, it is possible that any direct-current (DC) offset removal algorithm that introduces a substantial discontinuity in the stimulus waveform near ERP peaks of interest may similarly distort the waveform.

## MATERIALS AND METHODS

### Participants

Ten adults (53–77 years old; mean ± SD, 62 ± 8.04 years), all postlingually deafened, were recruited from the Maryland, Washington, DC, and Virginia areas. Nine participants used a Cochlear Ltd sound processor (Freedom or N5; Cochlear Ltd., Sydney, Australia) while one participant (CBY) used an Advanced Bionics CII sound processor (Sonova, Stäfa, Switzerland). Bilateral implanted users were tested in their better ear. All procedures were reviewed and approved by the Institutional Review Board of the University of Maryland. Participants gave informed consent and were paid for their time. See Table, Supplemental Digital Content 1, http://links.lww.com/EANDH/A342, for more detailed information about each participant.

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## Data Collection and Analysis

**Stimuli and Recording** • ERPs were elicited in response to a vowel /a/ synthesized at a 20-kHz sampling rate with a Klatt-based synthesizer (Klatt 1980). Two different durations were used: 170 and 400 ms (see Figure, Supplemental Digital Content 2, http://links.lww.com/EANDH/A343). Stimuli were presented unilaterally at a 1-Hz rate at the participant's self-reported most comfortable loudness level. Stimuli were delivered via direct audio input to the participant's clinical sound processor, which was set to their everyday program including typical sound processing features like automatic gain control. Participants with Cochlear Ltd devices had a stimulation rate of 900 pulses/sec/electrode; the participant with the Advanced Bionics device had a rate of 3712 pulses/sec/electrode. Using a Biosemi Active Two acquisition system (Biosemi B.V., Amsterdam, The Netherlands), EEG data were recorded at a 2048-Hz sampling rate with an antialiasing filter (low-pass filter with a −3 dB point at one-fifth of the selected sampling frequency). Data were recorded with an all-pass filter with the fixed amplifier gain imposed by the Biosemi system. The recordings were performed with a 32-channel cap organized according to the 10–20 International system (top of the head ground, earlobe contralateral to the CI stimulated as reference) with two additional electrodes used to track horizontal and vertical ocular artifacts of the eye contralateral to the ear that was tested.

**Data Analysis** • Data were converted into MATLAB format (MathWorks, version R2011b, Natick, Massachusetts) by using the function pop_biosig available in EEGLab (Delorme & Makeig 2004). Data analyses were limited to electrode Cz. Raw data were digitally band-pass-filtered off-line from 0.03 to 30 Hz (forward-backward fourth-order Butterworth filter) to eliminate the high-frequency transmission artifact generated by the CI (Mc Laughlin et al. 2013). Ocular artifacts were reduced using a regression-based electrooculography reduction method (Schlögl et al. 2007) in all participants except CBV (due to recording noise from the eye electrodes in that participant).

To remove the DC artifact or "pedestal" elicited by the current generated by the intracochlear electrodes, two different averages were computed: the average from the electrode of interest (Cz) and the average from the electrode that best represented the envelope of the stimulus recording artifact from the intracochlear electrodes. Because the presence of the DC pedestal resulted in larger amplitudes than what are normally recorded in individuals tested without CIs, the artifact rejection limits were adjusted up to ±800 µV if necessary to achieve 500 sweeps used in the average response. The stimulus recording artifact (usually recorded from the electrode most adjacent to the CI and chosen to best represent the features of the auditory stimulus) and the time domain of the neural response (Cz) were used as the arguments of a second-degree bivariate polynomial (Mc Laughlin et al. 2013). The second-degree bivariate polynomial was chosen because no substantial differences were noted when using either the second- or fourth-degree bivariate polynomial and this led us to opt for the use of the simplest model; and were combined in a matrix M to estimate the DC pedestal. As an alternative, a different matrix M was built by using the time domain of the neural response (Cz) and the envelope of the stimulus recording artifact as calculated by Mc Laughlin et al.: the waveform of the speech stimulus was first rectified and then low-passed filtered at 35 Hz using a zero-phase second-order Butterworth filter. The envelope was then decimated down to 2048 Hz and finally band-pass-filtered at 0.03 and 30 Hz using the same filter applied to the EEG data. An orthogonal-triangular decomposition was applied to each matrix M to find the least square solution of the bivariate polynomial. The estimated DC artifact for each electrode was then subtracted from each ERP, leading to the final ERP. See Figure, Supplemental Digital Content 3, http://links.lww.com/EANDH/A344, for a flowchart summarizing the key steps of our analysis; see Figure, Supplemental Digital Content 4, http://links.lww.com/EANDH/A345, for the topographical representation of the mean amplitude of the ERPs from each electrode recorded for pre-DC-pedestal artifact (A) and post-DC-pedestal artifact (B) removal for each participant; see Figure, Supplemental Digital Content 5, http://links.lww.com/EANDH/A346, for results from electrode Cz from each participant; see Figure, Supplemental Digital Content 6, http://links.lww.com/EANDH/A347, for results from electrode Cz for peaks P1, N1, and P2.

# RESULTS

Figure 1 shows the stimulus recording artifact for each participant tested with the 170- and 400-ms stimuli (panels A and B, respectively). There was a wide range of DC pedestal amplitudes with negative and positive polarities. An example of the negative amplitude of the estimated DC pedestal can been seen for participant CAX in Figure 2. The waveforms have been standardized and negative polarities (six participants) were inverted for visualization purposes in Figure 1.

The duration of the DC pedestal corresponded to the duration of the stimulus. For example, in Figure 2, the DC pedestals had durations that corresponded to the length of the stimulus. This resulted in an abnormal increase of the magnitude of the ERP amplitude, consistent with data reported by Mc Laughlin et al. (2013). Figure 2 also shows the effect of different stimulus duration on P2 peak morphology for CAX; Figure 3 shows the results from all the participants. The stimulus recording artifact rejection algorithm removed or minimized the DC pedestal in the participants tested, but created an additional "DC removal analysis artifact" at the onset and offset of the stimulus. The introduction of this DC removal analysis artifact can be best observed in Figures 2 and 3 at peak P2, which is known to occur between 150 and 250 ms in normal-hearing adult participants. At an individual participant level, it is clear from the figures that the DC removal analysis artifact affects the waveform at P2; however, some participants are more affected than others. The participants most affected were CAX, CBG, CAY, CAO, and CAQ.

We also sought to quantify the potential deleterious effects of the DC removal analysis artifact on response morphology using the different stimulus durations at the group level. Specifically, we observed an extremely sharp peak or spike in the time region of P2 for the 170-ms but not the 400-ms vowel. To quantify the slope, we calculated the first derivative of the response at the offset of the stimulus (150–180 ms), took the absolute value of the derivative function, and calculated the sum of this function. A paired *t* test revealed significantly higher derivative sums for the 170-ms compared to the 400-ms stimulus ($t_{[9]} = 2.28$, $p = 0.048$). Conversely, when the first derivative was calculated around the expected latency of peak P1 (30–70 ms) and N1 (70–150 ms), no significant differences were found between the 170- and 400-ms stimuli ($t_{[9]} = 1.03$, $p = 0.328$ and $t_{[9]} = 0.48$,

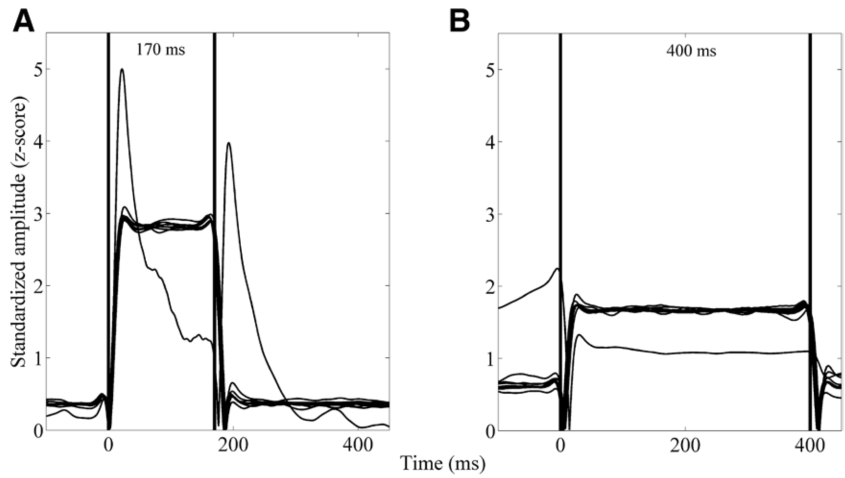


Figure 1. Stimulus recording artifact for each participant tested with the (A) 170- and (B) 400-ms stimuli extracted of the electrode that best represented the stimulus recording artifact. Vertical lines represent the onset (0 ms) and offset (170 and 400 ms) of the stimuli. The seemingly thick line results from superimposing the DC pedestals from all participants. This DC pedestal creates a positive (or negative) DC offset that lasts for the duration of the stimulus. DC indicates direct current.

$p = 0.64$, respectively). The time window used for P1 was based on standard latency reported in the literature; the window was also visually inspected for each individual to ensure it coincided with P1. We expanded the time window of N1 to accommodate the wide range of latencies of the participants. Means and standard deviations of the amplitude and latency for each peak are reported in Figure, Supplemental Digital Content 6, http://links.lww.com/EANDH/A347.

## DISCUSSION

The results of this study highlight how the offset of the stimulus may distort the morphology of evoked neural responses when removing the DC pedestal stimulus recording artifact that occurs in people with CIs. Although our analysis used the Mc Laughlin et al. (2013) method, DC removal analysis artifact could potentially be a problem for any DC artifact removal method, including independent component analysis (Viola et al. 2012), and we therefore recommend caution when interpreting evoked-response morphology in the temporal window immediately after the offset of the stimulus recording artifact. In our case, we were interested in analyzing the P1-N1-P2 complex in response to the vowel /a/. The use of the 170-ms stimulus led to corruption of P2 because the stimulus offset occurred when this peak is typically elicited, 150–250 ms after stimulus onset. Specifically, the waveform distortion and DC removal analysis artifact are best observed in Figures 2 and 3 in most of the participants (CAX, CBG, CAY, CAO, and CAQ), which show the introduction of a steep positive (or negative) deflection and two short and sharp peaks in contrast to the expected single long and smooth peak. In participant CBV, the DC removal analysis artifact was so dominant that P2 was completely replaced by a single spike-like peak. Note that the morphology of P1 and N1 was preserved, as their latencies were temporally removed from

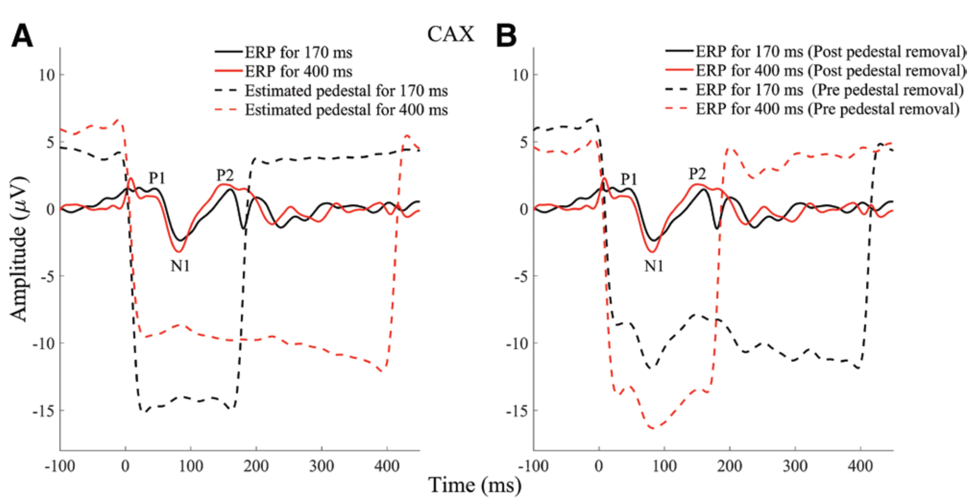


Figure 2. ERPs from electrode Cz for a single participant (CAX) elicited by the 170-ms (solid black) and the 400-ms (solid red) stimulus. The estimated DC pedestal for the respective stimuli are represented by dashed lines. The main peaks have been labeled P1, N1 and P2. The offset of the 170-ms stimulus created a negative deflection in P2 near 180 ms. The same DC removal analysis artifact was not seen with the 400-ms stimulus. DC indicates direct current; ERPs, event-related potentials.

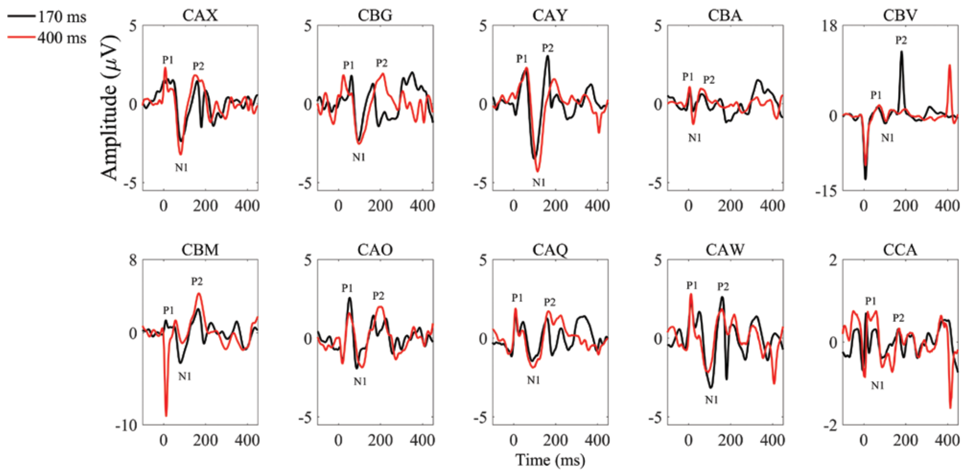


Figure 3. ERPs from electrode Cz elicited by the 170-ms (black) and the 400-ms (red) stimulus for individual participants. The P2 peak was often corrupted with the 170-ms stimulus, while the late offset of the 400-ms stimulus prevented DC removal analysis artifact from altering the shape of P2. DC indicates direct current; ERPs, event-related potentials.

the onset and offset of the stimulus such that the DC pedestal removal only affected their amplitudes. Although we used only one stimulus and specific removal algorithm, the DC removal analysis artifact may be problematic for any stimulus for which the onset or offset overlaps with a particular peak of interest.

Our observation appears to contrast with Mc Laughlin et al.'s (2013) conclusions, that is, "the DC estimation procedure robustly attenuates the artifact even when neural response and stimulus offset overlap in time" (Mc Laughlin et al. 2013, p. 90). The difference in conclusions between the two studies is easily explained; the Mc Laughlin et al. study focused on peak attenuation and did not look at morphology. In our study, we found that the DC removal analysis artifact associated with a 170-ms stimulus might indeed elicit a peak at around 170 ms, thus disrupting the expected P2. The differences in P2 morphology are unlikely to be caused by the use of low sampling frequency recording, as Mc Laughlin et al. showed that their method can be implemented even with most commonly used low-rate acquisition systems. It is important to point out that even in Mc Laughlin et al., the morphology of the ERP elicited in response to a 100-ms stimulus differs from the one elicited using a 300-ms stimulus (see Figure 4, Mc Laughlin et al., 2013, p. 87). However, in that case, the offset of the stimulus was so late that it had only a limited effect on the "tail" of P2, making the differences of the ERP to different stimuli harder to visualize. In our case, the artifact was more pronounced, as we used a stimulus whose offset (170 ms) degraded P2 at its very origin, thus significantly compromising the morphology of this peak in its entirety.

Note that substantial DC removal analysis artifact was not observed in all of the participants (participants CBA, CBM, CCA, and CAQ; Fig. 3); nonetheless, it remains an important issue that needs to be taken into consideration when performing cortical recordings and data analysis. We strongly advise choosing the length of the stimulus to be much longer than the ERP of interest to minimize the possibility that the offset of stimulus recording artifact produces a DC removal analysis artifact that occurs at the time of specific peaks of interest. If P1 is the ERP of interest, we would recommend avoiding stimuli whose offset is in the 20–80 ms range; if N1 is the ERP of interest, we would recommend avoiding stimuli whose offset is in the 80–150 ms range; if P2 is the ERP of interest, we would recommend avoiding stimuli whose offset is in the 150–250 ms range. Although we used a simple stimulus, we believe the effects generalize to any stimulus, for which the onset or offset overlaps with a particular peak of interest.

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The authors have no conflicts of interest to disclose.

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