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The effect of polarity order and electrode-activation order on loudness in cochlear implant users

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Abstract: This study examined the interaction between polarity and electrode-activation order on loudness in cochlear implant users. Pulses were presented with the polarity of the leading phase alternating or constant across channels. Electrode-activation order was either consecutive or staggered. Staggered electrode-activation orders required less current for equal loudness than consecutive orders with constant polarity. Consecutive electrode-activation orders required less current than staggered orders with alternating polarity. The results support the hypothesis that crosstalk between channels can interfere with or facilitate neuronal activation depending on polarity.

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1. Introduction

Cochlear implants provide hearing by stimulating the auditory nerve with electrical current. Typical cochlear implant stimulation consists of electrical pulses, which are presented sequentially from different electrodes (12 to 22 depending on the manufacturer; Wilson *et al.*, 1995). Sequential pulses can interact at the level of the auditory nerve when pulses occur close in time and stimulate (at least some of) the same auditory nerve fibers (Favre and Pelizzone, 1993; Boulet *et al.*, 2016). These temporal interactions can result in interference and facilitation between pulses. One factor that affects temporal interactions is the polarity order of the pulses (de Balthasar *et al.*, 2003; Karg *et al.*, 2013; Macherey *et al.*, 2017).

Pulses are typically symmetric and biphasic with each phase having opposite polarity (an anodic phase and a cathodic phase). Opposite polarity phases can interfere with each other in stimulating auditory nerve fibers, which is evidenced by findings that physiological thresholds are lower with monophasic than with biphasic pulses (Shepherd and Javel, 1999). Consistent with this, psychophysical studies have shown lower thresholds and most comfortable loudness levels (MCLs) when pulses have larger interphase gap durations and are alternating monophasic or pseudo-monophasic rather than biphasic (Carlyon *et al.*, 2005; van Wieringen *et al.*, 2005; Macherey *et al.*, 2006). The order of the polarity phases in clinical speech processing strategies is constant across pulses (i.e., pulses are either all anodic first or all cathodic first) such that adjacent phases of sequential pulses have opposite polarity, which may result in interference across pulses. Nevertheless, opposite polarity phases within each pulse are used to maintain charge balance, which is necessary for biological safety (Shepherd *et al.*, 1999).

In contrast, pulses can be presented with the polarity order of the phases alternating across pulses (i.e., the first pulse is cathodic first, the second pulse is anodic first,…). When the polarity alternates across pulses, pulses have been shown to facilitate each other. Thresholds and in some cases, MCLs are lower with alternating polarity compared to constant polarity across pulses (de Balthasar *et al.*, 2003; Karg *et al.*, 2013; Macherey *et al.*, 2017). This facilitation is presumably due to neuronal integration of charge from adjacent phases with the same polarity (Boulet *et al.*, 2016; Macherey *et al.*, 2017). The effect of alternating polarity across pulses on thresholds has been shown to disappear when pulses are separated by approximately 100 to 300 μs presumably due to neuronal dissipation of charge over time (de Balthasar *et al.*, 2003; Karg *et al.*, 2013). Because cochlear implant stimulation makes use of high pulse

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rates, pulses in some cases, occur contiguously in time. Thus, the facilitative effect of alternating polarity across pulses could potentially be used to improve power efficiency of cochlear implants due to lower current amplitude requirements (e.g., Schatzer *et al.*, 2015).

One way to alter the extent of interference or facilitation between pulses is to manipulate the distance between sequential pulses. Sequential pulses presented from electrodes spaced farther apart stimulate fewer of the same auditory nerve fibers (e.g., Hughes and Stille, 2010). Thus, crosstalk between channels (i.e., channel interactions) is presumably reduced. With multi-electrode stimulation, the manipulation of electrode-activation order is a way to change the distance between sequential pulses and presumably the extent of temporal channel interactions. The use of staggered (i.e., non-consecutive) as opposed to consecutive electrode-activation orders would likely reduce interference and facilitation due to greater distance between sequential pulses (Wilson *et al.*, 1995).

In this study, we examined the extent to which polarity order affects loudness with multi-electrode stimulation. We manipulated electrode-activation order to vary the extent to which sequential pulses stimulate the same auditory nerve fibers. We hypothesized that staggered as opposed to consecutive electrode-activation orders would result in lower MCLs when pulses are presented with constant polarity due to reduced interference. In contrast, we hypothesized that consecutive as opposed to staggered electrode-activation orders would result in lower MCLs with alternating polarity due to greater facilitation.

2. Methods

2.1 Participants and equipment

Participants included six adults with Advanced Bionics cochlear implants. Participants C101, C107, C110, C113 had HiFocus 1J electrode arrays. Participants C114 and C124 had HiFocus Mid-Scala electrode arrays. Participants' ages ranged from 33 to 81 (mean = 62 years, SD = 18). All participants had used their cochlear implant for at least four years. Five out of six participants had post-lingual onset of hearing loss. Participant C110 was identified with hearing loss at one year of age and was fit with hearing aids at 1.5 years of age.

2.2 Stimuli

Stimuli consisted of 500-ms trains of biphasic pulses with 32-μs phase durations and 0-μs interphase gaps. The phases of each pulse were opposite in polarity [i.e., one anodic phase (A) and one cathodic phase (C)] and were presented in monopolar mode. Pulses were presented at a rate of 900 pulses per second per electrode. MCLs were first found using single-electrode stimulation with cathodic-first pulses. With multi-electrode stimulation, 16 electrodes were stimulated sequentially in frames. In each frame, each electrode was stimulated once. There was no delay between sequentially stimulated electrodes aside from a delay between the last stimulated electrode in a frame and the first stimulated electrode in the next frame. The order of electrode activation within each frame was either consecutive or staggered. The consecutive electrode-activation order was apex-to-base, i.e., 1, 2, 3,…, where lower numbers refer to electrodes located more apically along the electrode array (referred to as 1-2-3). The staggered electrode-activation orders were either 1, 5, 9, 13, 2, 6, 10, 14, 3, 7, 11, 15, 4, 8, 12, 16 (referred to as 1-5-9) or 1, 9, 2, 10, 3, 11, 4, 12, 5, 13, 6, 14, 7, 15, 8, 16 (referred to as 1-9-2). Pulses were either constant or alternating in polarity across sequentially activated electrodes. In the constant-polarity conditions, pulses consistently had the cathodic phase first (Con-CA) or the anodic phase first (Con-AC). In the alternating-polarity conditions, electrodes with odd activation orders presented anodic-first pulses and electrodes with even activation orders presented cathodic-first pulses (Alt-1) or vice versa (Alt-2). To be clear, alternation in polarity were always across electrode. That is, on a given electrode for any particular stimulus, the polarity order of the phases of each pulse remained constant. Figure 1 shows schematics of example stimuli. The left-hand panel shows a single frame of a stimulus in the 1-2-3 electrode-activation order and Alt-1 polarity. The middle panel shows a single frame of a stimulus in the 1-5-9 electrode-activation order and Alt-2 polarity. The right-hand panel shows a single frame of a stimulus in the 1-9-2 electrode-activation order and Alt-1 polarity.

2.3 Procedure

Using cathodic-first pulses, the experimenter raised the current on single electrodes in 5- to 10-μA steps until the participant indicated that loudness was at MCL, which

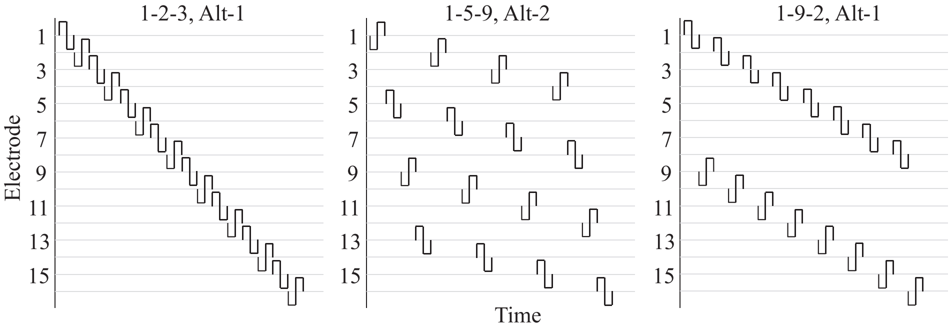

Fig. 1. Schematics of single frames of example stimuli. The left panel shows the 1-2-3 electrode-activation order in the Alt-1 polarity. The middle panels whos the 1-5-9 electrode-activation order in the Alt-2 polarity. The right panel shows the 1-9-2 electrode-activation order in the Alt-1 polarity.

corresponded to a six on a loudness scale (where eight was maximum acceptable loudness). MCL was measured for electrodes in a random order for each participant. Subsequently, loudness was balanced across all electrodes by sequentially stimulating electrodes in sets of four at MCL. The participant told the experimenter how to adjust the levels of the electrodes so that the loudness was equal across electrodes.

Using multi-electrode stimulation, loudness mapping was conducted for each combination of electrode-activation order (1-2-3, 1-5-9, 1-9-2) and polarity condition (Con-CA, Con-AC, Alt-1, Alt-2). The experimenter raised the current on each electrode in dB re current for loudness-balanced single-electrode MCLs. The participant indicated when loudness was barely audible, soft, most comfortable, loud but comfortable, and at maximal comfort. The order in which the conditions were loudness mapped was randomized for each participant.

The experimental task was a loudness balancing task. Within each trial, listeners heard two intervals which were presented continually. The first interval was the reference stimulus which consisted of the Con-CA polarity in the 1-2-3 electrode-activation order at MCL. The second interval was the variable stimulus, which was any combination of polarity condition and electrode-activation order. The interval of silence between the reference and variable stimulus was approximately 0.64 s. The interval between the variable stimulus and the next iteration of the reference was approximately 1.1 s. The participant turned a knob to adjust the current amplitude of the variable stimulus in 0.1 dB steps such that the loudness matched that of the reference. The current amplitude limits of the variable stimulus were the barely audible and maximal comfort levels previously determined. Conditions were presented in blocks with each condition occurring twice in each block, once with the variable stimulus starting at soft and once at loud but comfortable, in a random order. Conditions were newly randomized across blocks. Each listener conducted at least three blocks (six trials per condition).

The current amplitude in dB re the reference (Con-CA, 1-2-3 at MCL) was calculated for each combination of polarity condition and electrode-activation order. This value was consistent across electrodes. The data were averaged across trials within conditions for each participant. We conducted a two-way repeated measures analysis of variance to evaluate polarity (4 levels), electrode-activation order (3 levels), and the polarity ×electrode-activation order interaction. Pairwise t-tests (two-tailed) were conducted for all electrode-activation orders within each polarity condition and for all polarity condition within each electrode-activation order. A Holm-Sidak correction was applied to the p-values for each family (all pairwise comparisons of levels of a factor within a level of another factor) of pairwise comparisons. Only significant (adjusted p-value < 0.05) comparisons are reported. No differences were expected between the two alternating polarity conditions due to the similarity of the two conditions; however, statistical tests were conducted with the two alternating polarity conditions as separate levels.

3. Results

Figure 2 shows the current amplitude required for equal loudness as a function of the polarity condition. Each panel shows the data from an individual participant except for the last panel, which shows the group average. Electrode-activation order is indicated by the shading of the points. The Con-CA polarity in the 1-2-3 electrode-activation order was not significantly different from zero [$t(5) = -0.94$, $p = 0.39$; mean $= -0.085$,

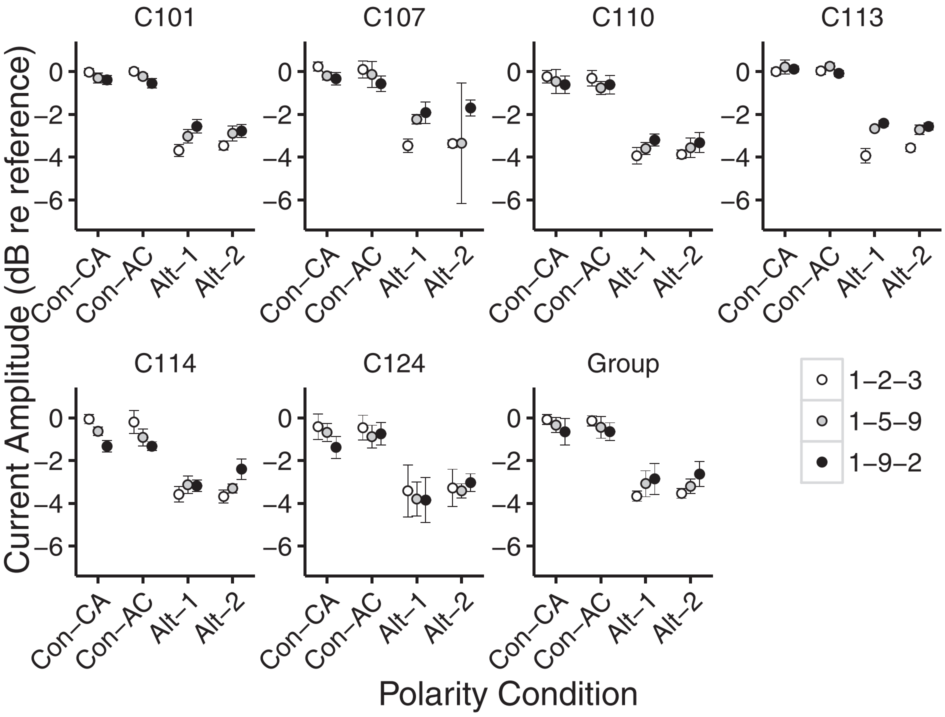

Fig. 2. Current amplitude (dB re the reference of the loudness balancing task, i.e., the Con-CA, 1-2-3 condition at MCL) as a function of polarity condition. The first six panels show data from individual participants. The last panel shows the group average. Electrode-activation order is indicated by the shading of the points. Error bars show 95% confidence intervals.

SD = 0.22], which was expected because this was the reference stimulus. The main effect of polarity was significant [$F(3, 30) = 457.33$, $p < 0.001$]. The main effect of electrode-activation order was not significant [$F(2, 30) = 0.85$, $p = 0.45$]. The polarity × electrode-activation order interaction was significant [$F(6, 30) = 13.33$, $p < 0.001$].

The significant polarity × electrode-activation order interaction was further investigated with pairwise t-tests. First, the differences between electrode-activation orders for the Con-CA and Con-AC polarities are described. The 1-9-2 activation order required significantly lower current than the 1-2-3 activation order for the Con-CA polarity [$t(30) = 3.08$, $p = 0.012$] and the Con-AC polarity [$t(30) = 2.75$, $p = 0.028$]. With the Con-CA polarity, the 1-2-3, 1-5-9, and 1-9-2 activation orders required on average −0.085 dB (SD = 0.22), −0.34 dB (SD = 0.33), and −0.66 dB (SD = 0.59), respectively, to maintain equal loudness. Similarly, with the Con-AC polarity, the 1-2-3, 1-5-9, and 1-9-2 activation orders required on average −0.14 dB (SD = 0.22), −0.45 dB (SD = 0.48), and −0.65 dB (SD = 0.40), respectively, to maintain equal loudness. These results indicate that with constant polarities, a greater distance between sequentially stimulated electrodes results in lower current-amplitude requirements.

Next, the differences between electrode-activation orders for the Alt-1 and Alt-2 polarities are described. The 1-2-3 activation order required significantly lower current than the 1-9-2 activation order in the Alt-1 polarity [$t(30) = 4.41$, $p < 0.001$] and the Alt-2 polarity [$t(30) = 4.89$, $p < 0.001$]. The 1-2-3 activation order required significantly lower current than the 1-5-9 activation order for the Alt-1 polarity [$t(30) = 3.21$, $p = 0.006$]. The 1-5-9 activation order required significantly lower current than the 1-9-2 activation order with the Alt-2 polarity [$t(30) = 3.09$, $p = 0.008$]. For the Alt-1 and Alt-2 polarity conditions together, the 1-2-3, 1-5-9, and 1-9-2 activation orders required on average −3.61 dB (SD = 0.22), −3.14 dB (SD = 0.45), and −2.74 dB (SD = 0.61), respectively, to maintain equal loudness. These results indicate that with alternating polarities, a smaller distance between sequentially stimulated electrodes results in lower current-amplitude requirements.

Finally, the differences between the polarity conditions (Con-CA, Con-AC, Alt-1, and Alt-2) are described. Significant differences were only found when comparing constant- and alternating-polarity conditions (Con-CA vs Alt-1; Con-CA vs Alt-2; Con-AC vs Alt-1; Con-AC vs Alt-2). Specifically, alternating-polarity conditions required significantly lower current than constant-polarity conditions for each of the three electrode-activation orders [for each of 12 significant comparisons, $t(30) > 11.76$, $p < 0.001$]. This indicates that an effect of polarity was present with all electrode activation orders, even with the 1–9-2 electrode-activation orders in which sequential pulses were presented from electrodes eight to nine electrode spaces apart (8.8 to 9.9 mm along the HiFocus 1J electrode array; 8 to 9 mm along the HiFocus Mid-Scala electrode array). One limitation of this study is the small sample size. We cannot assume that the results generalize to the greater population of individuals with cochlear implants. However, it can be seen in Fig. 2 that the results are fairly consistent across the individuals that were tested.

4. Discussion

In this study, we compared the current required to produce a given loudness (MCL) when the order of the polarity phases alternated across pulses and when the order of the polarity phases was constant across pulses. Electrode-activation order was manipulated to vary the extent of temporal channel interactions.

Alternating polarity conditions required lower current than constant polarity conditions in all electrode-activation orders examined. Additionally, alternating polarity conditions required lower current when sequential pulses occurred from electrodes that were closer, i.e., presumably when sequential pulses stimulated more of the same neural fibers (e.g., Hughes and Stille, 2010). The results can be explained by the idea that pulses facilitated each other in neuronal activation (Boulet *et al.*, 2016). The results are consistent with previous studies that have shown thresholds are lower with alternating compared to constant polarity orders (de Balthasar *et al.*, 2003; Karg *et al.*, 2013; Macherey *et al.*, 2017). The results are also consistent with the finding that MCLs can be lower when polarity alternates across pulses on single electrodes (Macherey *et al.*, 2017). The difference in MCLs with alternating compared to constant polarity conditions was at most 3.5 dB on average, which occurred with the consecutive electrode-activation order. The finding that MCLs with alternating polarity conditions were on average 2 dB lower than those with constant polarity conditions even with the 1-9-2 staggered electrode-activation order, is consistent with findings that spread of excitation is broad with cochlear implant stimulation (e.g., Hughes and Stille, 2010). The reduction in MCLs with alternating polarity conditions compared to constant polarity conditions can be examined with reference to the reduction that results from doubling phase durations, which has been found to be 5.58 dB at maximum stimulation levels for narrow phase durations (Bonnet *et al.*, 2012). Doubling phase duration is similar to the case in which all pulses in the alternating polarity conditions occur from the same electrode and therefore presumably have 100% overlap. The reduction in current amplitude observed in the present study with alternating polarity orders is presumably smaller than 5.58 dB due to incomplete overlap of the neural populations stimulated by sequential pulses. Channel interactions can be estimated by the current difference between constant and alternating polarity conditions to maintain equal loudness relative to 5.58 dB (i.e., current difference in the 100% overlap condition). Using this metric, we would estimate that with the alternating polarity, channel interactions were 63% on average with the consecutive electrode-activation order and 36% on average with the 1-9-2 staggered electrode-activation order.

In contrast, constant polarity conditions required lower current when sequentially presented pulses occurred from electrodes that were farther apart (1-2-3 vs 1-9-2 electrode-activation order). This finding suggests that pulses interfered with each other in neuronal activation. Previous studies examining the effect of increasing the distance between electrodes with dual-electrode stimulation have found inconsistent effects on loudness (Tong and Clark, 1986; McKay *et al.*, 1995; McKay *et al.*, 2001). However, unlike the present study, these studies used a time delay between pulses, which likely reduced the interference between pulses. Introducing a long enough time delay between pulses would likely eliminate the effect of electrode-activation order observed in the present study. The difference between the staggered and the consecutive electrode-activation orders with constant-polarity conditions was at most 0.54 dB on average. This number is smaller than the difference between the staggered and the consecutive electrode-activation orders with alternating-polarity conditions, which was at most 0.87 dB, suggesting there may be a larger effect of distance between sequential pulses on temporal channel interactions with alternating compared to constant polarity conditions. This number (0.54 dB) is also smaller than the difference between the constant and alternating-polarity conditions, which ranged from 2 to 3.5 dB on average. This suggests that reducing interference by staggering electrode-activation order is less effective at reducing current than the facilitative effect produced by alternating polarity across pulses.

No difference was found in the current required between cathodic-first (Con-CA) and anodic-first (Con-AC) constant polarity conditions. This is consistent with previous findings that failed to show a difference in loudness between cathodic-first and anodic-first symmetric biphasic pulses (Macherey *et al.*, 2017). However, it is unlike the findings with asymmetric pulse shapes, which have shown lower current requirements for MCL with anodic-dominant pulse shapes in humans (Macherey *et al.*, 2006; Carlyon *et al.*, 2013).

The finding that alternating polarity conditions reduced current suggests alternating polarity across pulses could potentially be used to improve power efficiency of cochlear implants (e.g., Schatzer *et al.*, 2015). However, there are a number of reasons that the present implementation of alternating polarities may not adequately convey speech information. First, channel interactions change when polarity alternates across pulses of different electrodes. Neurons which are stimulated by each of two electrodes may be activated more with alternating compared to constant polarity orders. This could have a detrimental effect on transmission of spectral information. Further investigation is needed to determine how spread of excitation changes when polarity alternates across channels and if alternating polarity orders can be implemented in a way that preserves transmission of spectral information. Second, anodic-adjacent and cathodic-adjacent pulses may not result in the same reduction in current (Macherey *et al.*, 2017), which could distort the spectral profile. Third, any pulse that is not preceded by another pulse of sufficient current amplitude would sound too quiet. This could cause variability in loudness depending on the stimulation pattern, especially because the effect of polarity was large (up to 2.9 to 3.8 dB across participants) relative to the dynamic ranges of the participants (roughly estimated to be between 4.3 and 12.7 dB in the constant polarity conditions). Thus, a more selective implementation of alternating polarity orders may be required to preserve speech information. Additionally, we assume that the electrical dynamic range is maintained with alternating polarity conditions. However, we did not systematically measure thresholds; therefore, the difference in dynamic range between constant and alternating polarity orders still needs to be verified.

In summary, the results of the present study support the idea that pulses presented contiguously in time with a constant order to the polarity phases interfere with each other in producing loudness. Staggering the electrode-activation order reduces the interference such that lower current is needed for a given loudness. Alternating the order of the polarity phases across pulses makes it such that pulses facilitate each other in producing loudness. This facilitation is reduced when the electrode-activation order is staggered.

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