Loudness summation using focused and unfocused electrical stimulation

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Abstract: With a cochlear implant, when stimulation from multiple channels is interleaved, the perceived loudness is greater than the loudness associated with any of the individual channels presented in isolation. This phenomenon is known as loudness summation. This study examined if loudness summation with monopolar and tripolar stimulation were equivalent at two loudnesses and two spacing configurations. Results suggest that loudness summation is similar for monopolar and tripolar modes. However, larger summation differences were observed for softer sounds and louder sounds with a larger spatial separation. The results are consistent with the idea that loudness summation is dependent on channel interaction and have implications for implementing current-focused processing strategies.

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1. Introduction

The loudness of a pulse train presented on a single electrode of a cochlear implant (CI) grows monotonically with stimulus amplitude (Tong *et al.*, 1983; Shannon, 1985). Generally, the loudness growth function is similar for monopolar (MP), bipolar (BP) (e.g., Landsberger and Galvin, 2011), and tripolar (TP) stimulation modes (Berenstein *et al.*, 2010). When multiple electrodes provide interleaved stimulation as is typical of most modern CI processing strategies, the loudness of the interleaved stimulus is greater than the loudness provided by the stimulation from any one of the individual electrodes presented in isolation. This phenomenon is known as loudness summation (Tong and Clark, 1986; McKay *et al.*, 1995). The degree of interaction from the stimulation on each electrode may affect the degree of loudness summation. Given the recent interest in changing stimulation modes to reduce spread of excitation (SOE) from individual channels to improve speech processing, (e.g., Landsberger and Srinivasan, 2009; Landsberger *et al.*, 2012; Smith *et al.*, 2013; Berenstein *et al.*, 2008; Saoji *et al.*, 2013; Srinivasan *et al.*, 2013) it is important to understand how changes in stimulation mode effect loudness summation. If loudness summation is different for different stimulation modes, then a change in stimulation mode may produce a change in loudness growth in a speech processor.

McKay *et al.* (2001) compared loudness summation with MP and BP stimulation. They found that with comfortably loud sounds (roughly 80% of the dynamic range), loudness summation was similar for the two stimulation modes. However, for quieter sounds (50% of the dynamic range) loudness summation was greater for MP stimulation than BP stimulation. Assuming a fixed amplitude growth map for each

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electrode in a sound coding strategy, this data suggests that loud sounds will be presented equally loudly with BP or MP sound coding strategies. However, the data also suggests that due to the greater loudness summation with MP stimulation at quiet levels, quiet sounds will be presented louder to a CI user using a MP stimulation mode than a BP stimulation mode. The small differences between loudness summation with MP and BP pulse trains might be explained by the finding that BP stimulation does not seem to provide a narrower SOE compared to MP stimulation (Chatterjee, 1999; Kwon and van den Honert, 2006; Bonham and Litvak, 2008; Schoenecker *et al.*, 2012). Other stimulation modes, such as TP (Landsberger *et al.*, 2012; Fielden *et al.*, 2013), quadrupolar virtual channel (Srinivasan *et al.*, 2010), and phantom electrode (Saoji *et al.*, 2013), have been shown to provide a reduced SOE relative to MP stimulation at a fixed loudness. Computational modeling predicts that a phased array configuration also produces a reduced SOE (Frijns *et al.*, 2011). Each of these stimulation modes reduces SOE by simultaneously stimulating out-of-phase on multiple electrodes to reduce current spread. Because TP stimulation has been specifically shown to improve speech performance in noise (Srinivasan *et al.*, 2013), the present study focuses on TP stimulation.

In TP stimulation, reduced SOE is accomplished by delivering a fraction of the current on the active electrode to the two flanking adjacent electrodes. The amount of current delivered to the flanking electrodes is determined by a coefficient σ. A total of $\sigma/2$ of the active electrode current is delivered to each flanking electrode. The remaining current is returned to a common ground extra-cochlear electrode. The current to the flanking electrodes is presented out-of-phase to the current delivered to the active electrode. In the present paper, a value of $\sigma = 0.75$ was used for all TP stimuli.

The motivation for this study was to determine how different loudness summation is for MP and TP stimulation modes, in order to provide insight into the effect of changing stimulation mode on loudness in a speech processing strategy. The degree of loudness summation for MP and TP stimulation when seven adjacent electrodes were stimulated, in an interleaved manner, at both soft and medium loudnesses were compared. This condition is clinically relevant as clinical speech processing typically provides stimulation on adjacent electrodes. A comparison was also made for seven alternating electrodes stimulated in an interleaved manner at the same loudness. This condition provides additional insight into loudness summation for the two stimulation modes because it magnifies any differences in channel interaction from a change in SOE. However, this condition is less representative of a typical clinical speech processing strategy as every other channel is deactivated.

2. Methods

The amplitudes required to create equally loud single pulse trains at soft and medium loudnesses were calculated for most electrodes in both MP and TP ($\sigma = 0.75$) modes. Two different multi-electrode configurations, consisting of channels individually providing equally loud stimulation, were created (Fig. 1, top). The MP multichannel configurations were then loudness balanced to the TP multichannel configurations. The differences in amplitude between the pulses in the loudness-balanced multichannel MP configuration and the non-balanced multichannel configurations were used as a measure of the difference in loudness summation between MP and TP stimulation. For further details, see below.

2.1 Subjects

Seven post-lingually deafened Advanced Bionics CII or HiRes 90 K CI users with HiFocus 1J electrodes participated in the study. All subjects gave informed consent to the project as approved by the St. Vincent Medical Center Institutional Review Board. All subjects were tested at the House Research Institute.

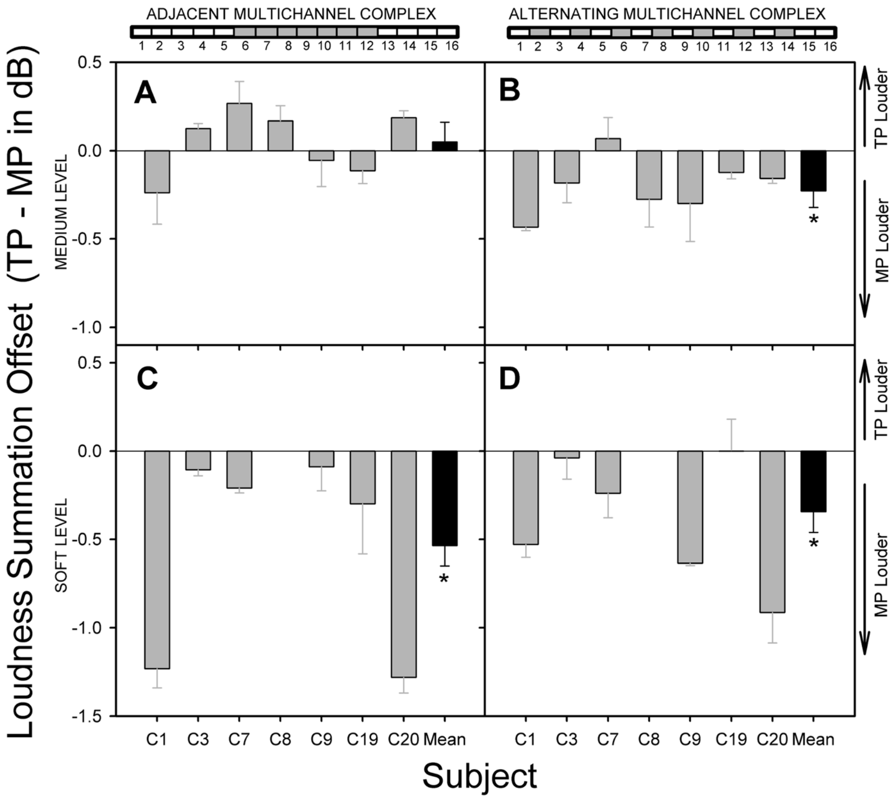

Fig. 1. Bar plots show average loudness summation offset (from three repetitions) in dB, along with the standard error for each subject tested (gray bars). The mean offset for all subjects is shown as the last bar (black) of the bar plots for each multichannel complex. Results are shown for a medium loudness level: (a) results for the adjacent multichannel complex; (b) results for the alternating multichannel complex. Average loudness summation offset at a soft loudness level: (c) results for the adjacent multichannel complex; (d) results for the alternating multichannel complex. Asterisks denote significant results.

2.2 Stimuli

The stimuli consisted of biphasic pulse trains at a stimulation rate of 450 Hz, phase duration of 140 μs, and no inter-phase gap. The duration of each stimulus was 300 ms. The stimuli were presented in either MP or TP configurations.

2.3 Procedure

Single channel loudness estimations. Loudness estimation was determined for individual electrodes 2, 4, 6, 7, 8, 9, 10, 11, 12, and 14 both in MP and TP configurations for all seven subjects. Subjects indicated the estimated loudness of stimuli using a scale ranging from 0 to 10 provided by Advanced Bionics. Stimuli were presented initially below threshold and gradually increased in 5 μa steps until the "maximal comfortable level" was reached. For each stimulus, the amplitudes corresponding to loudness described as "barely audible" (1), "soft" (3), "medium" (5), "most comfortable" (6), and "maximum comfortable level" (8) were recorded. Two loudnesses were used for the experiment: a "soft" (3) and a "medium" (5) level. Because the magnitude of loudness summation was not known *a priori*, a conservative medium (5) loudness was used as the single channel loudness for creating the louder multi-electrode complexes used in this experiment. This reduced the possibility of the stimuli reaching an uncomfortable loudness when multiple channels were added together.

Single channel loudness balancing. All TP electrodes were loudness balanced to a reference electrode (electrode 8) in TP mode, set to each of the reference levels (soft, 3 and medium, 5) measured previously. A 2AFC double staircase method (1-up 3-down and 1-down 3-up) was used to loudness balance the stimuli. Ten reversals were measured and the average of the last six reversals was defined to be the balanced loudness for each staircase. The final balanced loudness was the average of both staircases. The step size for the first two reversals was set at 1 dB, and at 0.5 dB for the last eight reversals. Three repetitions of the loudness balancing procedure were made for each electrode pair at the soft and medium loudness. The average of the three repetitions was determined to be the matched loudness value. Each individual electrode in MP mode was loudness balanced to the measured loudness value for the corresponding electrode in TP mode using the same previous procedure. Again, the loudness balancing procedure was repeated three times per electrode and the average of all the three loudness estimates was determined.

Multichannel loudness balancing. Two different sets of multichannel complexes were created as shown in Fig. 1 (top). Stimulation amplitudes on each electrode in a complex were set to the previously loudness balanced levels at soft or medium loudness amplitudes. Stimulation from each electrode in each multichannel complex was presented sequentially. Both complexes remained within the comfortable dynamic range for each subject. The first multichannel complex consisted of stimulation on seven adjacent electrodes: 6, 7, 8, 9, 10, 11, and 12 (1.1 mm spacing between electrodes) for most subjects. We refer to this complex as the adjacent multichannel complex. Subject C1 used electrodes 8, 9, 10, 11, 12, 13, and 14, because C1 was unable to reach a comfortably loud level with electrode 7 in TP mode. The second multichannel complex consisted of even numbered active electrodes: 2, 4, 6, 8, 10, 12, and 14 for most subjects (2.2 mm spacing). Subject C19 had electrodes 13–16 disabled in his clinical map so electrodes 5, 6, 7, 8, 9, 10, and 11 were used for his adjacent multichannel complex and 2, 4, 6, 8, and 10 were used for his alternating multichannel complex. The amplitudes of the pulses in the newly created complexes were called the uncompensated amplitudes to distinguish from complexes with different amplitudes measured later.

The loudness of the MP multichannel complexes was balanced to the corresponding TP complexes at both the soft and medium levels using a procedure similar to the procedure used for single-channel loudness balancing (2AFC, double staircase). A step size of 0.5 dB was used for the first two reversals and a step size of 0.2 dB for the last eight reversals. The average of the last six reversals was used as an estimate of the amplitudes of the TP complex that produce an equally loud percept as the corresponding MP complex. Three repetitions of the loudness-balancing procedure were made for each complex based on both the soft and medium loudness. The average of the three repetitions was determined to be the matched loudness value for the TP multichannel complexes. The differences (in dB) between the loudness balanced TP multichannel complexes and the uncompensated amplitudes for the same multichannel complexes were called the loudness summation offset. If loudness summation is equivalent for both MP and TP stimuli, then the loudness summation offset should be equal to zero $\pm$ noise. If TP summation provides a greater degree of loudness summation, then the loudness summation offset should be greater than 0. Conversely, if TP summation provides a smaller degree of loudness summation, then the loudness summation offset should be less than 0.

3. Results

The loudness summation offsets between MP and TP stimulation for each subject and each condition were calculated and plotted in Fig. 1. The loudness summation offset was typically below zero for both soft level complexes [Figs. 1(c) and 1(d)] as well as the medium alternating multichannel complex [Fig. 1(b)], indicating that loudness summation tends to be greater for MP stimulation in these conditions. However, no consistent offset was observed for the medium adjacent multichannel complex [Fig. 1(a)].

Of the 25 loudness summation offsets measured, 20 of them were negative, indicating a significant result ($p = 0.0041$) with a two-tailed binomial test.

At the medium loudness, the loudness summation offset was ± 0.5 dB or less for both multichannel complexes tested and for all seven subjects. This suggests that loudness summation is very similar for both types of stimulation modes at this level. For the medium loudness adjacent multi-channel complex [Fig. 1(a)], there is no clear pattern in the amplitude offset for the seven subjects tested. The individual offsets are no larger than 0.25 dB. The mean shift for all subjects is below 0.1 dB (black bar). A one-sample Wilcoxon signed ranked test showed that loudness summation offset was not different than 0 ($Z = 0.845$, $p = 0.398$).

For six of the seven subjects tested (all but C7), MP loudness summation is larger than TP loudness summation [Fig. 1(b)]. The loudness summation offset was found to be significantly different from 0 using a one-sample Wilcoxon signed ranked test ($Z = -2.197$, $p = 0.028$). The mean shift for all seven subjects is close to 0.2 dB, suggesting that although there is indeed a statistically significant difference in loudness summation, the magnitude of the difference is small, approaching the resolution of an implant.

The loudness summation offset is larger for MP stimulation at softer levels for both the adjacent [Fig. 1(c)] and alternating [Fig. 1(d)] multichannel complexes. Although the loudness summation offsets are larger than observed at a medium loudness [i.e., Figs. 1(a) and 1(b)], the mean offset at the softer level is less than 0.6 dB for both complexes. One-sample Wilcoxon signed rank tests show that the difference is significant for both the adjacent ($Z = -2.201$, $p = 0.028$) and alternating ($Z = -1.992$, $p = 0.046$) multichannel complexes at the soft level.

4. Discussion

This study demonstrates that summation is similar for MP and TP configurations at a comfortable, medium loudness. These results are consistent with McKay *et al.* (2001) who found no significant difference in loudness summation between MP and BP pulses at a loud level. It has been shown that in response to a pulse train that MP and BP spreads of excitation are similar both psychophysically (Kwon and van den Honert, 2006) and physiologically (Schoenecker *et al.*, 2012). At the medium level in the present experiment no significant difference in loudness summation between MP and TP stimulation was found for the adjacent multichannel complex (1.1 mm separation), however, a significant difference for the alternating multichannel complex (2.2 mm separation) was found. With a softer level of stimulation, McKay *et al.* (2001) found BP loudness summation to be greater than MP summation. Conflictingly, this study found that at softer loudness MP loudness summation is larger than TP summation for both multichannel complexes regardless of electrode separation. One factor potentially effecting loudness summation is that with a broader spread of excitation, neurons in the region between channels are more likely to still be in a refractory state when the next pulse is presented than with a narrower SOE. This prediction is consistent with the results from McKay *et al.* (2001) but not with the present results. It is worth noting that the results in the present study are representative of the overall effect of loudness summation in a cochlear implant as the complexes represent an extended cochlear region. However, an examination of loudness summation at multiple local cochlear regions would likely reveal variability in loudness summation across the cochlea due to inhomogeneous neural survival and spread of excitations. Similarly, the differences in loudness summation between MP and TP stimulation modes would likely be increased with electrode spacing.

McKay *et al.* (2001) concluded that the degree of loudness summation was dependent on the degree of overlap between stimulation from each channel. If this is true, then the smaller the channel interaction, the smaller the loudness summation. Therefore, if TP stimulation provides a reduced channel interaction relative to MP stimulation, then TP stimulation should produce a narrower SOE. Our results in three of the four tested conditions (soft level with adjacent and alternating multichannel complexes and medium level alternating multichannel complex) are consistent with these conclusions. However, the results for loudness summation in the medium level adjacent multichannel complex either contradict the idea that reduced channel interaction reduces loudness summation or suggest that in this condition TP stimulation does not sufficiently reduce the SOE. It is possible that the reduction in spread from TP stimulation is greater 2.2 mm away from the peak of stimulation than at 1.1 mm away from the peak, resulting in less forward masking between adjacent channels. This idea seems consistent with the forward masked SOE data from Fielden *et al.* (2013) as well as the loudness summation results from McKay *et al.* (2001). It is less consistent with similar data from Landsberger *et al.* (2012). If so, this might explain why a difference in loudness summation is observed for the medium alternating multichannel complex (as there is greater separation between channels) but none is observed for the medium adjacent multichannel complex. Similarly, it is possible that at quieter levels TP stimulation provides a greater reduction in SOE, which would explain why a difference in loudness summation is only observed at the soft level for the adjacent multichannel complex. However, Fielden *et al.* (2013) found no effect of loudness level on reduction in spread of excitation with TP stimulation.

The results from this experiment are worth considering when changing stimulation modes in a speech processing strategy. Because in the adjacent multichannel complex the difference between loudness summation in MP and TP stimulation was greater at the soft level than at the medium level, the loudness growth function of a speech processing strategy using focused stimulation is likely to be different than with an unfocused strategy. Loudness growth at quieter levels is likely to be less steep for TP stimulation. If all other parameters are fixed across strategies, stimuli presented relatively high in the patient's dynamic range will be perceived as similarly loud with a current focused and unfocused strategy. However, sounds that would be presented relatively low in the dynamic range would be perceived as louder with unfocused stimulation than with focused stimulation. Effectively, this means that the unfocused stimulation mode would provide a more compressed signal than the focused stimulation. However, the effect should be small considering the average difference in loudness summation offset between the medium and soft levels is less than 0.6 dB. It is unclear whether or not the small changes in loudness growth with a TP strategy are beneficial or detrimental. However, if it were necessary to maintain equivalent loudness growth, any differences in the loudness-growth function could be compensated by a change in amplitude mapping function in the speech processing strategy. It is worth noting that although it is harder to extrapolate to a speech processing strategy with only two channels used in McKay *et al.* (2001), their results are also consistent with these conclusions.

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