

# LOUDNESS SUMMATION FOR TWO CHANNELS OF STIMULATION IN COCHLEAR IMPLANTS: EFFECTS OF SPATIAL AND TEMPORAL SEPARATION

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An experiment with four implantees with the Mini System 22 device was undertaken to measure the loudness summation across two channels of stimulation, with stimuli in which the current pulses were delivered alternately to each channel. The effects of varying spatial separation, temporal separation, and extent of stimulation were investigated. It was found that the absolute amount of summation varied among subjects, and was in general independent of electrode separation, except for a reduction at zero separation. Widening of the spatial extent of the stimulation did not have a consistent effect. There was a reduction in summation for all subjects at zero electrode separation when the time between the two pulses was increased from less than 1 millisecond to 2 milliseconds. In conclusion, loudness summation did not appear to be highly dependent on parameters that affect the spatial current spread in the cochlea. Further study of the effect of temporal parameters on loudness may help to quantify interaction between stimulation channels.

## INTRODUCTION

Most currently available cochlear implant sound processors utilize sequential pulsatile stimulation of a number of different scala tympani locations.<sup>1</sup> The use of sequential rather than simultaneous stimulation avoids the direct summing of currents from different cochlear locations, which may lead to unpredictable effects on loudness. Loudness summation still occurs in sequential stimulation, due to neural and psychophysical channel interactions. It has been previously postulated<sup>2,3</sup> that the amount of loudness summation across two channels activated sequentially could be used as a measure of the effect of neural interaction due to overlap of the two stimulated neural populations. The firing activity of neurons that are subject to currents from both stimuli will depend on their refractory properties, causing the total neural activity for the combined stimulus to be less than the sum of activity from the two individual stimuli. This means that there would be a predicted reduction of loudness summation for two channels with overlapping stimulus areas. However, the effect of spatial or temporal separation of two stimuli, and of stimulation extent (mode of stimulation), has remained largely uninvestigated. The aim of this experiment was to answer two questions. First, how useful is a loudness summation measurement as an indicator of the amount of channel interaction? Second, can the amount of loudness summation be predicted from the spatial and temporal parameters of the stimulation? These questions are of some importance to the development of speech-processing strategies, as the current trend in speech processors is to use pulses of stimulation that are closer both in temporal and spatial dimensions.

## SUBJECTS AND STIMULI

Four adult implantees (subjects 1 to 4) who have the Mini System 22 device (manufactured by Cochlear Pty Limited) took part in this study. These were one woman and three men, ages 53, 74, 52, and 40, respectively. All are postlingually profoundly deaf, and had no useful residual hearing before implantation. Subjects 2 and 3 both suffered progressive loss of hearing over a long period due to otosclerosis, subject 1 was

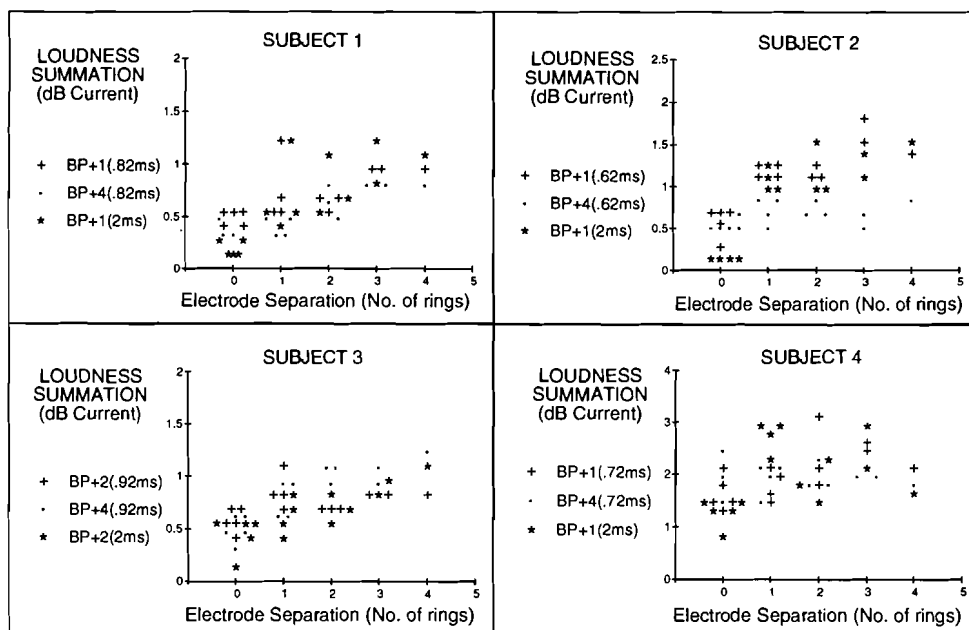
deafened at the age of 14 by presumed meningitis, and subject 4 suffered a rapidly progressive loss of hearing of unknown origin in the 2 years preceding his implantation. All subjects had available the full 22 electrode rings of the implanted array, except subject 3, whose three most apical rings were deactivated because of unpleasant nonauditory sensations.

The Mini System 22 cochlear implant consists of an intracochlear array of 22 active electrodes, spaced at intervals of 0.75 mm, which are activated by an implanted receiver-stimulator. The receiver-stimulator receives digitally encoded signals from a speech processor via a transcutaneous inductive link. In these experiments the speech processor was interfaced with an IBM-compatible personal computer that, with specifically designed software, was used to control the parameters of stimuli in each experiment and to record the subject's responses.

Bipolar stimulation was used in this experiment. Each bipolar pair consists of an active (more basal) electrode ring and a ring for the current return path. The spatial extent of the stimulation was defined as the distance between the two members of a bipolar pair. Two spatial extents were used, being 1.5 and 3.75 mm (denoted BP + 1 and BP + 4) for all subjects except subject 3, who used 2.25 and 3.75 mm (BP + 2 and BP + 4). In dual-electrode stimulation, two such bipolar pairs were activated. The spatial separation of the channels in the dual-electrode stimuli was defined as the distance between the two active members of the two bipolar pairs. Separations between 0 and 3.0 mm (up to 4 electrode rings) were investigated in this experiment.

Each stimulus was a train of biphasic current pulses of constant amplitude and pulse width, and had a duration of 500 milliseconds (ms). In the case of single-electrode stimuli, the pulses had a constant rate of 250 Hz. In the case of the dual-electrode stimuli, the overall repetition rate was 250 repetitions per second, with two biphasic pulses generated in each repetition period, one for each of the two component electrode pairs. The pulse width used for each subject was held constant throughout the study at a value that allowed comfortable

Loudness summation for dual-electrode stimuli plotted against electrode separation for four subjects with three different combinations of spatial extent and inter-electrode delay. Loudness summation is given as ratio reduction (in decibels) of current needed to maintain loudness equal to that with component single-electrode stimuli. Electrode separation is given in number of rings (spaced at 0.75-mm intervals). Data at each separation have been spread horizontally for clarity.



loudness to be achieved at moderate current values. These were 150, 50, 200, and 100 microseconds for subjects 1 to 4, respectively. For the dual-electrode stimuli, two time delays (interelectrode delay) were used between the onset of the pulses at the two electrode positions. The larger time delay was 2 ms for each subject, which put the second pulse halfway through the repetition period (effective 500-Hz overall rate). The smaller time delay was governed by the pulse width used for each subject together with a fixed delay of 0.48 ms after the offset of the first of the two biphasic pulses. This produced interelectrode delays of 0.82, 0.62, 0.92, and 0.72 ms for subjects 1 to 4, respectively.

#### METHODS

For each subject, five adjacent electrode positions were selected that were in the apical half of the array. Initially, the smaller spatial extent was chosen (2.25 mm for subject 3 and 1.5 mm otherwise). Single-electrode stimuli were constructed for each of these five positions, and each of these was loudness-balanced (see below) with the stimulus in the middle position. Next, dual-electrode stimuli were constructed using all possible pairs of different electrode positions and at least three pairs using the same electrode twice. The spatial separations in the dual-electrode stimuli thus ranged from 0 to a maximum of 4 electrode rings (3.0 mm). The interelectrode delay was first set at the smaller of the two values used for each subject (see above). The currents in these dual-electrode stimuli were initially set to equal those in the single-electrode stimuli at the corresponding electrode positions. Each dual-electrode stimulus was then loudness-balanced with the same reference as the single-electrode stimuli. When the two currents in the dual-electrode stimulus were adjusted simultaneously, they were changed in equal ratios. The loudness summation for each dual-electrode stimulus was then calculated as the ratio reduction of the currents in the dual-electrode case in order to maintain the same loudness as the component single-electrode stimuli.

The loudness balancing procedure involved two comple-

mentary steps in order to account for any subject bias effects. First, the reference stimulus current was set to produce a comfortably loud sensation, and the subject adjusted the current in the variable stimulus (by means of an unmarked knob) until the two stimuli were considered to be equal in loudness. Second, the current of the variable stimulus was fixed at the level arrived at in the first step, and the current in the reference stimulus was adjusted to produce equal loudness. If there was no bias, then the final value of the reference current equaled its initial value. If there was a difference in the two reference current values, the bias effect was assumed to be equal in both steps, and the current of the balanced variable stimulus was adjusted by half any such difference. The whole loudness-balancing procedure was then repeated, and an average of the two results was used.

The experiment was then repeated twice for two different stimulus conditions: the first time using the larger spatial extent (3.75 mm) and keeping the interelectrode delay the same; the second time using the larger interelectrode delay (2 ms) and keeping the spatial extent to the initial smaller value. Each set of data was inspected to see the effect of spatial separation, and the three sets of data for each subject were compared to see the effect of widening the spatial extent or increasing the interelectrode delay.

#### RESULTS AND DISCUSSION

A three-way analysis of variance with subject, separation, and stimulus condition as variables was performed, and the results showed highly significant effects for all three variables and for all interaction terms. The significant interaction terms mean that the effects of separation were subject- and stimulus condition-dependent, and the stimulus condition effect was also subject-dependent. In order to obtain a more interpretable analysis, a two-way analysis of variance was performed for each individual subject (with separation and stimulus condition as the variables). Any significant effect was further evaluated with a post hoc test of critical significant difference (using the standardized range distribution) to see which

separations or stimulus conditions were different. The results of these analyses will be discussed with the aid of the raw loudness summation data shown in the Figure. The loudness summation values for each subject in the three stimulus conditions tested are shown in separate panels of this Figure. The vertical axes represent the amount of loudness summation for each dual-electrode stimulus, and the horizontal axes represent the spatial separation within the stimulus.

Before looking at the detailed statistical analysis, there are three general observations that may be made about the data. First, loudness summation was always positive; ie, if currents were kept the same, the dual-electrode stimulus was always louder than the component single-electrode stimuli. This is what would be expected if there was no direct current summation. Second, the absolute amount of summation observed, when measured in ratio current reduction, varied a great deal across subjects (compare subjects 3 and 4 in the Figure, for example). If the summation were expressed as a fraction of the subject's electrical dynamic range, the difference would widen even further. The largest ratio current reductions (subject 4, up to 3 dB) were observed with the smallest dynamic ranges (about 3.5 dB), and subject 3, with the widest dynamic ranges (8.5 to 9.0 dB), had some of the smallest summation values (generally less than 1 dB). Third, there was a considerable spread of summation values for the same subject across stimuli with equal spatial separation and extent and interelectrode delay (ie, for stimuli differing only in electrode position). There are two possible reasons for this. The method of measuring loudness summation may have produced a large variance in the data. This is unlikely to account for all the variation, however, as the variance in repeated loudness summation measurements was generally less than 0.3 dB. Alternatively, factors that affect the degree of summation (current spread, for example) may vary significantly with small changes in electrode position.

The two-way analysis of variance for subject 1 showed a significant effect of separation ( $F[4,42] = 11.28, p < .001$ ), the summation at zero separation being less than at a separation of two or more rings, and the summation at one ring separation being less than that at three rings. There was no significant effect of stimulus condition, or interaction between separation and condition. For subject 3, there was also a significant effect of separation ( $F[4,44] = 16.37, p < .001$ ), with summation at zero separation being significantly less than that at all other separations, and the summation at one-ring separation being not significantly different from that at all larger separations. This subject also had a significant effect of stimulus condition ( $F[2,44] = 4.44, p = .02$ ), with the longer interelectrode delay showing less summation than the other two conditions. Although there was not a significant interaction term, the effect is only seen in the raw data for the two smallest separations (where most of the data points lie). For the other two subjects, there was a significant interaction term between stimulus condition and separation. In the case of subject 4, there was no significant effect of stimulus condition. An effect of separation ( $F[4,42] = 5.14, p = .003$ ), along with a significant interaction effect with stimulus condition, were both removed by omitting the data for larger interelectrode delay. The reason for this can be seen in the Figure, which shows that this subject did not show any variation of summa-

tion with separation (even at zero separation), except in the case of stimuli with the larger interelectrode delay. In that case, the summation was reduced for zero separation and increased for a separation of one ring over other summation values at these separations. For subject 2, separation, stimulus condition, and interaction terms were all significant. The reason for this can be seen by inspecting the data: the BP + 4 data show less summation than the other conditions, but not at zero separation; there is a reduction of summation at zero separation, but not in the BP + 4 condition. Omitting the BP + 4 data did not remove the significance of the main effects and interaction effect, since the two BP + 1 sets of data showed less summation for the longer interelectrode delay, but only at zero separation.

To summarize the results of the analysis, there was a clear effect of electrode separation on loudness summation, with a reduction evident when the separation was zero. However, only subject 1 showed an increase in summation when going from one ring to further distances, and there were cases in which there was no change of summation at all with separation (subject 2 in the BP + 4 condition, and subject 4 in the two conditions with short interelectrode delay).

It would be expected that if summation depended strongly on the overlap of stimulation areas, then the wider spatial extent would show the same summation as the narrow spatial extent at zero separation, but the summation would increase more slowly as the separation increased. However, only subject 2 showed a significant effect of spatial extent, with reduced summation at distances greater than zero, as expected. However, the summation did not increase for distances greater than one ring.

The effect of increasing the interelectrode delay was more consistent among subjects, but only occurred at the smallest separations. At zero separation, the increased delay caused a reduction in loudness summation (ie, moving the pulses apart in time made the sound softer). This effect is opposite to that expected if refractoriness of neurons stimulated by both pulses was the major factor governing the reduction in loudness summation at small separations. Two possible mechanisms for this effect may be temporal loudness integration at small time delays, or the presence of a neural excitatory (rather than inhibitory) effect of the first pulse (ie, the first pulse may excite a number of neurons but not cause them to fire). Furthermore, the data show a possible correlation between the size of this effect and the difference in the interelectrode delay. For example, compare subjects 2 and 3 in the Figure, who have the largest and smallest differences in the interelectrode delay, and also the largest and smallest differences in summation at zero separation. This possible correlation would have to be further investigated in a within-subject experimental design, however. At larger electrode separations, there was no effect of interelectrode delay, except for subjects 3 and 4 at a separation of one ring. Subject 3 still showed a small reduction of summation for the greater delay, and this is consistent with the wider spatial extent he was using. Subject 4 showed an increase in summation at a separation of one ring (the only subset of the data that did show an increase of summation for a greater delay).

The possible reasons for subject 4's showing patterns of

loudness summation different from those of the other subjects are difficult to surmise. His much greater overall summation values, and the absence of any electrode separation effect, are probably not due to his adjacent electrode positions' stimulating discrete sets of neurons, as his electrode discrimination is somewhat worse than that of the other subjects.

### CONCLUSIONS

This experiment showed that loudness summation did not depend in a simple way on the parameters of stimulation that might affect the overlap of stimulation areas. Furthermore, it varied considerably among subjects and in the same subject at slightly different electrode positions. A consistent reduction of summation was seen only when the two stimuli completely overlapped (zero separation), and changing the extent of the stimulation had effects that varied greatly among subjects.

Increasing the interelectrode delay caused a reduction in loudness summation at zero separation. Further research to study this last effect may yield some more useful information about the neural interactions within multiple-electrode stimuli.

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