Evidence of the enhancement effect in electrical stimulation via electrode matching (L)

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The ability to match a pulsing electrode during multi-electrode stimulation through a research interface was measured in seven cochlear-implant (CI) users. Five listeners were relatively good at the task and two could not perform the task. Performance did not vary as a function of the number of electrodes or stimulation level. Performance on the matching task was not correlated to performance on an electrode-discrimination task. The listeners may have experienced the auditory enhancement effect, and this may have implications for speech recognition in noise for CI users.
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I. INTRODUCTION

The "enhancement" effect occurs when a component of a complex tone is removed and reinserted, which increases the salience of the enhanced component by increasing the level of the target and/or diminishing the masking from adjacent frequency components (Viemeister and Bacon, 1982). Enhanced tones have improved detection thresholds (Viemeister, 1980), produce more forward masking of a probe tone than unenhanced tones (Viemeister and Bacon, 1982), produce interaural level differences in dichotic presentation (Byrne *et al*., 2011), and may be related to speech understanding in noise (Summerfield *et al*., 1987; Thibodeau, 1991). Perceptually, an enhanced tone can "pop-out" or be perceived as a perceptually separate auditory entity from the complex tone background, which has been verified with pitch matching (Hartmann and Goupell, 2006) and pitch comparison (Erviti *et al*., 2011).

Enhancement measured by forward masking seems to not occur in hearing-impaired (HI) listeners (Thibodeau, 1991). While HI listeners typically demonstrate abnormal adaptation processes (Bacon *et al*., 1989), there are at least two other possible explanations for the lack of enhancement in HI listeners. The first is poorer frequency selectivity from broadened auditory filters. The second is diminished fine-structure processing, because the enhancement effect has been shown to be phase dependent (Viemeister and Green, 1972; Hartmann and Goupell, 2006). If poor frequency selectivity or fine-structure processing are reasons that HI listeners do not demonstrate enhancement, one could hypothesize that enhancement would not occur for cochlear-implant (CI) listeners, who have extremely poor frequency resolution due to current spread and are not presented fine-structure information. On the other hand, CI listeners might show the effect because enhancement can occur for high-numbered unresolved harmonics (Hartmann and Goupell, 2006). The purpose of this work is to determine if CI listeners demonstrate enhancement using a task similar to the pitch-matching task of Hartmann and Goupell (2006).

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II. EXPERIMENT 1: MATCHING

A. Listeners and equipment

Seven listeners between 22 and 71 years were tested (mean age = 54 years). Five listeners had bilateral CIs and two had unilateral (IBS and IZA). Bilateral listeners chose their preferred ear for unilateral stimulation. All listeners had at least 2 years of experience using the CI in their tested ear and had 24-electrode Nucleus-type CIs (Nucleus24, Freedom, or N5). These CIs have 0.75-mm electrode spacing and are numbered such that the most apical electrode is 22 and the most basal is 1 (two electrodes are extra-cochlear). Listener IZA was the second author.

Stimuli were generated and experiments were run on a personal computer using MATLAB (the Mathworks). A Nucleus Implant Communicator (Cochlear Ltd.) delivered the stimuli directly to the implants.

B. Stimuli

The test stimulus was a multi-electrode, constant-amplitude stimulus except for one electrode, called the "target electrode," that was turned off and on. The electrodes that were not pulsed on and off are called the "background electrodes." Each on or off interval of the target electrode was 0.75 s and five intervals were played in the test stimulus. The target electrode began on and ended on. Monopolar biphasic electrical pulses (25-μs pulse duration, 7 μs between anodic and cathodic pulses) were presented at 1000 pulses per second (pps) per electrode. The order of stimulation across electrodes was interleaved to minimize channel interactions. When on, the stimulation level at each electrode in the test stimulus was near 80% or 50% of the dynamic range (DR), where the DR is the difference between a comfortable stimulation (C) and threshold (T) in logarithmic clinical current units. The number of electrodes in a test stimulus (N) was two (electrodes 4 and 20), four (2, 8, 14, and 20), six (2, 6, 10, 14, 18, and 22), or 11 (even numbers).

The matching stimulus was a single electrode presented at C for 1 s. All other stimulation properties were the same as the test stimulus. The difference in the test and matching stimulus level was chosen to approximately compensate for spread of excitation from background electrodes in the test stimulus.

C. Procedure

For each listener, T and C were measured by an experimenter on all 22 electrodes with constant-amplitude, 1000-pps, and 500-ms stimuli. Five-electrode sweeps on the C levels (100-ms interstimulus interval) and adjustments were performed to help ensure equal loudness across all 22 electrodes. Next, the test stimulus was presented to the listener at $80\%_{DR}$ for $N = 2$, 4, and 6. Five-electrode sweeps at $80\%_{DR}$ and adjustments were performed to help ensure equal loudness across electrodes. This procedure was repeated at $50\%_{DR}$ for $N = 6$ and 11.

For the main experiment, randomized conditions were tested in blocks. The number of trials per condition was $(2 + 4 + 6 = 12$ target electrode possibilities$) \times$ the number of repetitions (one or two, depending on listener preference). A trial consisted of the test stimulus followed by the matching stimulus that started at a randomly chosen electrode between 8 and 14; each stimulus was initiated by the listener. The listener controlled whether to play the same, higher-numbered, or lower-numbered electrodes, but did not know the matching-electrode number. If a listener attempted to adjust the matching electrode to non-existent electrodes, the edge electrode (22 or 1) was presented. The task was to adjust the matching electrode until it was the same as the target electrode in the test stimulus. Listeners were allowed to repeat the test and/or matching stimulus as necessary to ensure a good match. Listeners ended a trial after the match was suitable. Listeners performed several blocks. At least five trials per condition were collected for the nominally $80\%_{DR}$ conditions, and ten or more trials time permitting. After completion, four listeners performed nominally $50\%_{DR}$ conditions.

Before obtaining data, the task was explained to the listeners and several blocks of the nominally $80\%_{DR}$ conditions were performed, which served as training. There was no feedback, but listeners were encouraged to ask questions to make sure they understood the task. It was unclear if IBV understood the task, even after 4 hours of training. Unlike the other listeners, she never reported a pop-out, although she could hear an audible change in the test stimulus over time; all other listeners reported a pop-out in at least one of the conditions. Listener IZA was the most experienced listener because he was an author and spent a notable amount of time pilot testing the experiment.

D. Results

The data are shown in Fig. 1, where the closed symbols represent "misses." Misses are defined as an absolute difference between target and response electrodes greater than 4 (a cochlear distance of $0.75\,\text{mm} \times 4$ electrodes $= 3\,\text{mm}$), which was chosen to approximately correspond to the spread of current measured via spatial tuning curves for monopolar stimulation (Nelson *et al.*, 2008). Listeners IAJ, IBK, IBM, IBO, and IZA had the fewest misses and appeared to reasonably and consistently match the target electrode, indicating that they could identify the target electrode and were probably experiencing an enhancement or pop-out effect. Listeners IBS and IBV had the largest number of misses and showed little or no effect of target electrode on their responses. Separate one-way analyses of variance (ANOVAs) were performed on each of the five conditions. There was a significant effect of target electrode for each condition after correction for multiple comparisons ($p < 0.0001$ for all).

To determine the accuracy of the matching and summarize the data across conditions, we calculated two metrics: the second moment of the target-response difference (S) and the percentage of misses ($\%_{Miss}$). In ANOVAs using S and $\%_{Miss}$, there were no significant effects of N or DR ($p > 0.5$ for all). Therefore, the ability to match the target electrode may be independent of the number of active electrodes and stimulation level.

We performed a control experiment with IAJ, IBO, and IZA to validate that they were experiencing enhancement and not simply detecting amplitude modulation in the test stimulus. The matching task was repeated for $N = 6$, nominally $80\%_{DR}$ test stimuli with two intervals (target electrode off then on), making the test stimuli more similar to those used in previous enhancement experiments (Viemeister, 1980). We also tested two- and five-interval stimuli where a 200-ms silent gap was inserted between intervals. Normal-hearing (NH) listeners show about 10 dB of enhancement with a 200-ms silent gap after a stimulus adaptor (Viemeister, 1980). Data were analyzed in a two-way ANOVA with factors interval and gap. There was no difference between two- and five-interval stimuli [S: $F(1,12) = 0.12$, $p = 0.73$; $\%_{Miss}$: $F(1,12) = 0.33$, $p = 0.58$]. Stimuli with a gap had significantly larger values of S and $\%_{Miss}$ than those with no gap [S: $F(1,12) = 8.0$, $p = 0.022$; $\%_{Miss}$: $F(1,12) = 13.4$, $p = 0.006$]. For the gap conditions, IAJ, IBO, and IZA had $S = 63.5$, 65.6, and 14.4, respectively, when averaged over the number of intervals. These values can be compared to those of the listeners who showed no effect of target electrode in their responses when there was no gap; IBS and IBV had $S = 125.9$ and 51.0, respectively ($N = 6$ and $80\%_{DR}$, see Fig. 1). Also, IAJ, IBO, and IZA had $\%_{Miss} = 57.9$, 53.3, and 23.3% for the gap conditions while IBS and IBV had $\%_{Miss} = 70.0$ and 60.0% for no gap. Since S and $\%_{Miss}$ for IAJ and IBO when listening to test stimuli with a gap between intervals are near those for IBS and IBV who showed no effect of target electrode in Fig. 1, it appears that two of our three listeners lost the ability to perform the matching task when the gap was introduced.

III. EXPERIMENT 2: DISCRIMINATION

The ability of the listeners to perform the matching task may be related to their ability to discriminate individual electrodes. We performed an electrode-discrimination experiment to investigate this possible relationship.

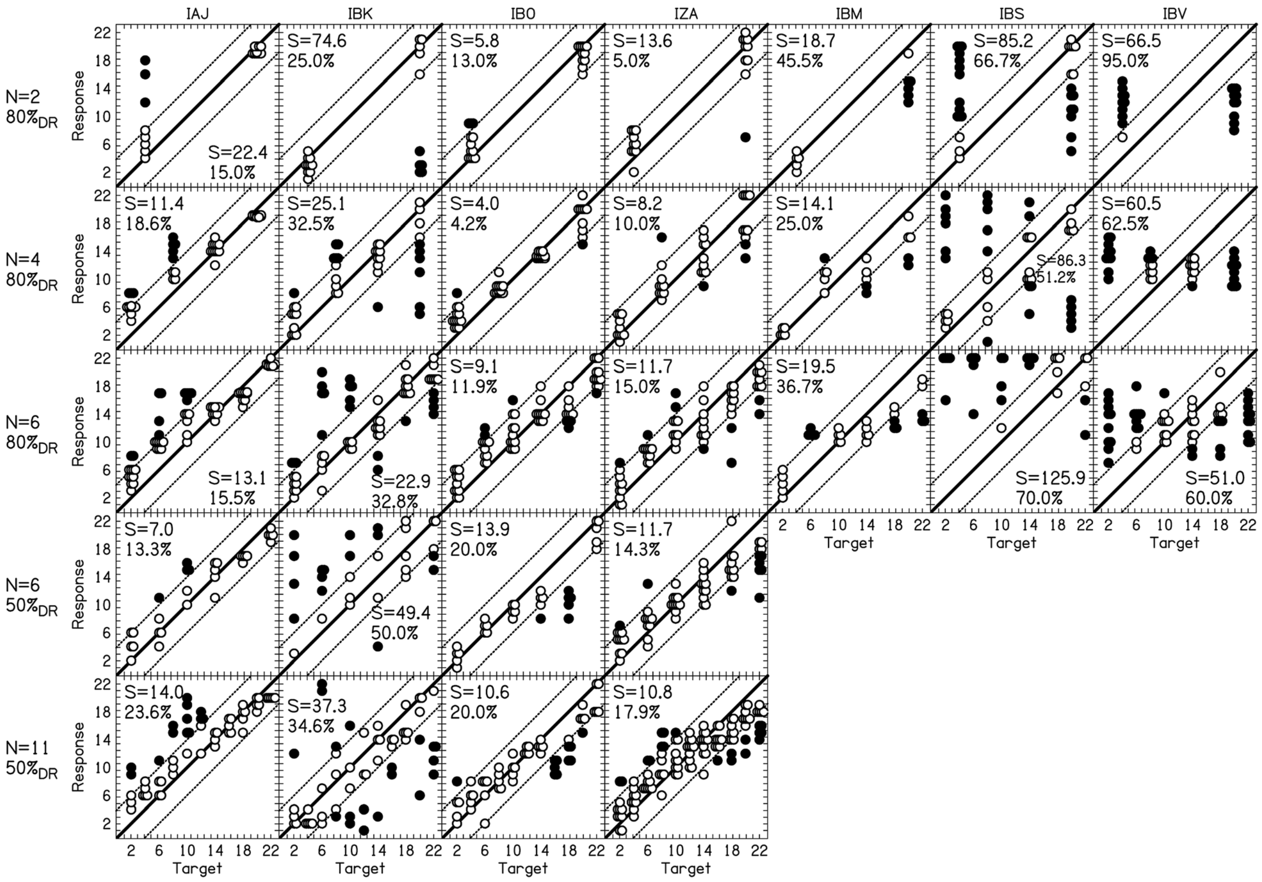

FIG. 1. Electrode responses as a function of target electrode for different number of electrodes (N) and stimulation levels. Each column represents a different listener. The solid line represents perfect electrode matching. The dotted lines show responses of ±4 electrodes; responses outside the dotted lines are shown with solid symbols and represent a "miss." The second moment of the target-response difference (*S*) and the percentage of misses are reported in each panel.

The listeners and equipment were the same as in experiment 1, except that IBM did not participate. The stimuli were single-electrode, 1000-pps, 500-ms, constant-amplitude pulse trains presented at nominally $80\%_{DR}$. The other properties of the stimuli were the same as in experiment 1. An electrode-discrimination task was performed for five reference electrodes (20, 16, 12, 8, and 4). Each reference electrode was compared to electrodes that were ± 1, ± 2, and ± 3 electrodes from the reference (except electrode 20 could not be compared to the non-existent electrode 23).

Listeners were given a two-interval, two-alternative forced-choice task without feedback. Each trial consisted of a reference and comparison electrode played in separate intervals with a 300-ms interstimulus interval. The order of reference and comparison electrode in the trial was randomized. The task was to indicate whether the place pitch of the second interval was higher or lower than the first. The percentage of correct responses (P_c) was calculated for each comparison where the correct answer for the higher pitch was associated with the lower electrode number (more basal) of the pair. Conditions were randomized in blocks. There were 10 trials per condition per block. Each listener completed at least four blocks.

The metric used to evaluate electrode discrimination was P_c minus 50% (to compensate for guessing) averaged over all five or six comparison electrodes for each reference electrode and is denoted "ED." For instances of negative ED values (i.e., pitch reversals), the absolute value was taken. The ED metric was linearly interpolated between reference electrodes to have a crude measure of electrode discrimination ability across the electrode array. Electrodes higher than 20 and lower than 4 were set to the same ED as electrodes 20 and 4, respectively. The average ED across all electrodes was calculated over the 22 individual electrode EDs. Linear regressions were performed between *S* (averaged over the three conditions) and average ED, and $\%_{Miss}$ and average ED. Including all six listeners, there was no relationship between *S* or $\%_{Miss}$ and average ED ($R^2 = 0.02$ and $R^2 = 0.07$, respectively). However, if IZA was omitted from the regression, there was a significant relationship between *S* or $\%_{Miss}$ and average ED ($R^2 = 0.42$ and $R^2 = 0.85$, respectively).

IV. DISCUSSION

Experiment 1 showed that five CI listeners could convincingly match an electrode that was turned off and on in an otherwise steady state background, analogous to the pitch-matching task of Hartmann and Goupell (2006), which demonstrated that a similar stimulus causes enhancement or a pop-out effect in NH listeners. The effect appeared to be independent of the number of electrodes in the test stimulus and of the stimulation level. We predicted no effect of stimulation level and changed it to test backgrounds with a large number of electrodes. We predicted that electrode-matching ability would decrease as N increased; furthermore, N = 11 would show no enhancement because the electrode spacing would be so small that current spread from the nearest active electrodes would remove any detectable notch in the spectrum. Surprisingly, electrode-matching ability was independent of spectral resolution because listeners performed the task just as well for N = 11 as for lower values. This result can be compared to the detection of static notches in multi-electrode stimulation. Goupell *et al.* (2008) showed that removal of a single electrode to make a spectral notch could be detected only 39% of the time by CI listeners in a forced-choice task. The listeners in that study had 2.4-mm electrode spacing, which is comparable to the 3-mm electrode spacing used in the N = 6 condition in this experiment. Apparently, a static notch in a sound spectrum (like in a profile analysis task) is not like a dynamic notch (like the one presented in this study) using electrical stimulation. The matching data of this study is also surprising because enhancement seemingly does not occur in HI listeners (Thibodeau, 1991). CI users can be considered an extreme case of HI listeners with extremely poor frequency resolution due to current spread and a lack of temporal fine structure because stimulation strategies do not present it. One explanation for this possible discrepancy between HI and CI listeners is that demonstrating enhancement depends on the task used to measure it.

We found that electrode-matching (experiment 1) and single-electrode discrimination (experiment 2) were not related unless IZA was omitted (who had one of the best matching performances but worst discrimination performance). It could be that our single-electrode discrimination is not an appropriate measure of spatial resolution for multi-electrode stimulation or that IZA's exceptional matching ability was due to much more exposure to the stimuli because he was an author.

To ensure that listeners were not simply detecting amplitude modulation in the test stimulus, we tested three listeners with stimuli that only had two intervals (off then on) and those with a 200-ms gap between intervals. There was no effect of the number of intervals, which makes us believe that our listeners were experiencing enhancement. However, adding a 200-ms silent gap between intervals significantly degraded performance as measured by S and $\%_{\mathrm{Miss}}$; these values for IAJ and IBO approached the values of IBS and IBV, who could not perform the matching task when there was no gap between the intervals. However, IZA could still perform the matching task, just not as well as when there was no gap between intervals. It may be that CI listeners experience recovery from enhancement at different time scales than NH listeners (Viemeister, 1980) or that IAJ and IBO needed more practice with the task, like IZA.

Carlyon *et al.* (2007), in one condition, asked CI listeners to "hear out" a single electrode in a 400-ms four-electrode stimulus (3-mm electrode spacing) where the onset of the target was delayed 200 ms compared to the other electrodes. In a forced-choice task, listeners were able to detect the delayed target compared to a stimulus with no delay, although the improvement was only 2%–11%. The analogous stimulus in our experiment would occur in the two-interval, no gap, N = 6, and nominally $80\%_{\mathrm{DR}}$ condition. Not inconsistent with Carlyon *et al.*, our data show listeners could reliably match the target electrode in this condition. Although Carlyon *et al.* attributed the weakness of the improvement to current spread, our data may speak against that argument as our listeners could still reliably match target electrodes for N = 11, where stimuli had a 1.5-mm electrode spacing and should experience even greater effects of current spread. The similarity of the stimuli in Carlyon *et al.* and this study does raise the question as to whether enhancement is occurring or whether some other grouping effect is being tested. Anecdotally, all seven listeners reported that they heard a change in the test stimulus over time and six reported that the target electrode popped-out from the background. For the listeners who could perform the task, this change was likely a spectrally local change in loudness. For the listeners who could not perform the task, it was likely a change in the overall loudness.

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