Research Article

Auditory Enhancement in Cochlear-Implant Users Under Simultaneous and Forward Masking

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ABSTRACT

Auditory enhancement is the phenomenon whereby the salience or detectability of a target sound within a masker is enhanced by the prior presentation of the masker alone. Enhancement has been demonstrated using both simultaneous and forward masking in normal-hearing listeners and may play an important role in auditory and speech perception within complex and time-varying acoustic environments. The few studies of enhancement in hearing-impaired listeners have reported reduced or absent enhancement effects under forward masking, suggesting a potentially peripheral locus of the effect. Here, auditory enhancement was measured in eight cochlear-implant (CI) users with direct stimulation. Masked thresholds were measured under simultaneous and forward masking as a function of the number of masking electrodes, and the electrode spacing between the maskers and the target. Evidence for auditory enhancement was obtained under simultaneous masking, qualitatively consistent with results from normal-hearing listeners. However, no significant enhancement was observed under forward masking, in contrast to earlier results with normal-hearing listeners. The results suggest that the normal effects of auditory enhancement are partially but not fully experienced by CI users. To the extent that the CI users' results differ from normal, it may be possible to apply signal processing to restore the missing aspects of enhancement.

Keywords: cochlear implants, enhancement, adaptation, context effects

INTRODUCTION

Auditory enhancement has been studied in many different ways over the past several decades (e.g., Schouten 1940; Wilson 1970; Viemeister 1980; Serman et al. 2008; Byrne et al. 2011, 2013; Carcagno et al. 2013b). One of the earliest quantifiable demonstrations of enhancement was via simultaneous masking (Viemeister 1980). This paradigm showed that the detection threshold for a target in the presence of a simultaneous masker (Fig. 1, left panel) could be decreased (improved) by up to 10 dB by presenting the masker (known as the precursor) prior to the masker-target combination (Fig. 1, middle panel). In principle, this effect could be explained by neural adaptation of the masker components by the precursor, enhancing the relative salience of the target. However, although adaptation is observed throughout the auditory pathways from the auditory nerve (Kiang et al. 1965; Smith 1979) to the auditory thalamus and cortex (Ulanovsky et al. 2004; Antunes et al. 2010), adaptation alone may be insufficient to account for enhancement. Adaptation of the masker components by a precursor would lead to an increase in the response to target, *relative* to the response to the masker components, but would not in itself lead to an *absolute* increase in the response to the target. This pattern of responses is not consistent with the available psychophysical data. For instance, an enhanced target component (i.e., with a precursor) produces more forward masking of a subsequent brief probe than an unenhanced target (Viemeister and Bacon 1982), sug-

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FIG. 1. Schematic diagram of conditions tested under simultaneous masking with masker components shown in black and the target component shown in red. In the MSK condition, no precursor is present. In the ENH condition, the precursor is present, which is expected to produce enhancement. In the CON condition, the

precursor is presented, but with the target component present, so that enhancement is not expected. Only the interval containing the target is shown.

gesting an absolute enhancement of the response to the target. Similarly, the enhanced target is judged to be louder than the unenhanced target, whereas the loudness of the masker components is not affected by the presence of the precursor (Wang and Oxenham 2016).

To explain the apparent absolute enhancement of the target, a mechanism termed “adaptation of inhibition” has been proposed (Viemeister and Bacon 1982). According to this mechanism, the masker components mutually inhibit the response to each other and to the target component. This inhibition decays (or adapts) over time, along with the neural response itself. Therefore, when the precursor is presented prior to the target, the inhibition of the target by masker components is reduced by the time the target is presented, leading to a larger response to the target than would have been the case if the precursor had not been presented.

From a physiological standpoint, absolute enhancement (as required to explain enhancement under forward masking) has not been observed at the level of the auditory nerve (Palmer et al. 1995) but has been reported at the level of the inferior colliculus (Nelson and Young 2010). However, some psychophysical evidence points to a more peripheral locus of the enhancement effect. For instance, enhancement is often stronger for an ipsilateral than for a contralateral precursor (Viemeister and Bacon 1982; Summerfield et al. 1984; Holt and Lotto 2002; Carcagno et al. 2012, 2013a). Also, enhancement appears to be reduced or absent in people with cochlear hearing loss, at least when measured using forward masking (Thibodeau 1991). Cochlear implants (CIs) provide an opportunity to test hypotheses related to the peripheral nature of enhancement. The CI bypasses the inner ear to stimulate the auditory nerve directly. Therefore, if there is a peripheral (cochlear) component to enhancement, it should not be present in CI users. Goupell and Mostardi (2012) reported that CI users were able to detect a component that was gated on and off within a continuous multi-component complex and related their observations

to the enhancement effect. However, it is not clear to what extent sensory enhancement is involved in this paradigm, as opposed to attention being drawn to the gated component (e.g., Moore et al. 2012). Wang et al. (2012) used a vowel-perception paradigm introduced by Summerfield et al. (1984) and showed that CI users experience some enhancement, but that it is reduced relative to that observed in normal-hearing listeners, most likely due to a loss of frequency selectivity.

By measuring enhancement with both forward and simultaneous masking, it may be possible to separate the putative mechanisms of adaptation from those of adaptation of inhibition. Specifically, adaptation alone should lead to a decrease in the response to the maskers prior to the onset of the target, potentially leading to an enhancement of the target, relative to the maskers. This could in turn lead to enhancement measured under simultaneous masking. In contrast, enhancement under forward masking requires an absolute enhancement of the response to the target component, which cannot be achieved via a simple adaptation mechanism but could be explained via adaptation of inhibition. Thus, if CI users exhibit only adaptation, then enhancement should be observed under simultaneous masking, but not forward masking. On the other hand, if CI users exhibit both adaptation and adaptation of inhibition, then enhancement should be observed in both simultaneous- and forward-masking paradigms.

EXPERIMENT 1: AUDITORY ENHANCEMENT USING SIMULTANEOUS MASKING

Subjects

Eight postlingually deafened adults were tested, all of whom had been implanted with Advanced Bionics CIs. Four subjects (D19, D27, D33, and D36) were bilaterally implanted, but only one ear (determined by user preference) was used in testing. According to surgeons' reports, full insertion of the electrode array (25 mm) was

achieved in all cases. Table 1 provides additional subject information. For the present study, stimulation was monopolar, with the active intracochlear electrode referenced to an electrode on the case of the internal receiver-stimulator.

Stimuli and Procedure

Experiments were controlled by a personal computer running custom programs written for the Bionic Ear Data Collection System (BEDCS; Advanced Bionics, Valencia, CA) controlled by MATLAB. The precursor stimuli were 500-ms pulse trains, while the masker and target stimuli were 200-ms pulse trains, of 32- μ s/phase, cathodic-first biphasic pulses, presented in monopolar mode at a rate of 2000 pulses per second (pps). The gap duration between the precursor (when present) and the masker/target complex was 20 ms, as short gaps between the precursor and masker are known to produce the largest enhancement effects (e.g., Viemeister 1980; Feng and Oxenham 2015).

First, the absolute threshold (THS) and the maximum acceptable loudness (MAL) were measured for each CI user on electrodes 2–14 for the 200-ms pulse trains. The THS was measured using a three-interval, three-alternative forced-choice task with a two-down, one-up adaptive procedure that tracks the 70.7 % point on the psychometric function (Levitt 1971). Correct-answer feedback was provided after each trial. The final step size was 10 μ A and the average current at the last six reversals of ten total reversals was taken as the THS for a particular run. The THS estimates from two separate runs were averaged to obtain a final THS value for each electrode and each subject. The MAL was measured using a one-up, one-down adaptive tracking procedure in which the sound was presented, followed by the question “Was it too loud?” A subject’s “no” or “yes” choice led to an increase or decrease in the signal level, respectively. As with the THS measurements, the final step size of the procedure was 10 μ A. The track terminated when the subject had responded that the intensity was too loud six

times, and the average current at the last six reversals points of the tracking procedure was calculated. The MAL estimates from two such runs were averaged to obtain a final value of MAL for each electrode and each subject. The dynamic range (DR) was then determined using the difference in current (μ A) between MAL and THS for each electrode of each CI user.

The masker level on each electrode was set to 30, 50, or 70 % DR with either 2 or 4 maskers that were placed symmetrically around the target electrode 8. The precursor/masker electrode spacing was set to 2, 3, or 6, where an electrode spacing of 6 means that the precursor/masker electrodes were electrodes 2 and 14, and an electrode spacing of 3 implies that the precursor/masker electrodes were 5 and 11 in the two-masker conditions and 2, 5, 11, and 14 in the four-masker conditions. The precursor was set to the same level as the masker.

In the main experiment, a two-interval, two-alternative forced-choice task was used in conjunction with a two-down one-up adaptive procedure that tracks the 70.7 % point on the psychometric function (Levitt 1971). On each trial, only one of the two intervals contained the target. The interval containing the target was selected at random on each trial with equal a priori probability. Initially, the target level was varied with a step size of 2 dB. After two reversals of the tracking procedure, the step size was reduced to 1 dB. After a further two reversals, the step size was reduced to its final size of 0.5 dB for the final six reversals. Threshold from each run was defined as the mean level at the last six reversal points. Each condition was tested on each subject a total of six times, and the threshold for each condition was the mean of those six thresholds in each condition.

The different test conditions are shown in Figure 1. The MSK condition contains just the masker and the target stimuli; the ENH condition contains a precursor stimulus, which is comprised of the same components as the masker; the CON condition provides a control in which the precursor comprises both the

TABLE 1

Subject information

Subject	Gender	Age (years)	CI use (years)	Etiology	Duration HL prior to implant (years)	ICS/electrode type
D02	F	63.4	11.6	Unknown	1	C-II/HFII
D19	F	53.6	8.9	Unknown	11	HR90K/HF1j
D24	M	63.3	5.9	Unknown progressive	27	HR90K/HF1j
D27	F	61.2	3.7	Otosclerosis	13	HR90K/HF1j
D28	F	64.4	10.4	Familial progressive SNHL	7	C-II/HFP
D33	M	73.9	0.5	Noise exposure; trauma	<1	HR90KA/HF1j
D34	F	72.8	1.4	Trauma; progressive	2	HR90K/HF1j
D36	F	54.2	1.2	High fever	Unknown	HR90K/HF1j

Presented in the columns from left to right are subject code, gender, age when tested for the present study, duration of implant use prior to the study, etiology of deafness, duration of bilateral severe-to-profound hearing loss prior to implantation, and the ICS/electrode type (HR90K = HiRes90K, HF90KA = HiRes90K Advantage, HFII = HiFocus-II array, HF1j = HiFocus 1J array, HFP = HiFocus array with positioner)

masker and the target components. The traditional enhancement effect in simultaneous masking (EE_{sim1}) is defined as the difference in target threshold (in dB) between the MSK and ENH conditions, i.e., the improvement in target threshold produced by introducing the precursor (e.g., Viemeister 1980). Another definition of enhancement, used by others, sometimes in tasks involving discrimination rather than detection (e.g., Carcagno et al. 2012; Feng and Oxenham 2015), is the difference (in dB) between the CON and ENH conditions, i.e., the improvement produced by removing the target component from the precursor (EE_{sim2}). The conditions were tested in random order for each subject and each repetition.

The statistical package SPSS was used to compute all statistical results reported below, and error bars in the figures represent standard errors of the mean. All reported analyses of variance (ANOVAs) include a Greenhouse-Geisser correction for lack of sphericity, where applicable.

Results

The pattern of results was quite similar across the eight listeners. Therefore, Figure 2 shows the average thresholds for all eight subjects in dB (re 1 μ A) for each condition as a function of the masker level. Each panel represents a different combination of electrode spacing (Sp2, Sp3, and Sp6) and number of maskers (Mk2 and Mk4). In addition, the average

unmasked THS and MAL for electrode 8 are shown by the solid and dashed lines, respectively. Figure 3 replots the data from Figure 2, showing masked thresholds relative to the masker levels used in each condition. In general, the thresholds of the ENH condition were the lowest, followed by MSK, and then CON. Thresholds also increased with increasing masker level and decreased with increasing electrode spacing. As the number of maskers increased from two to four for a particular electrode spacing, the thresholds also tended to increase.

A three-way repeated-measures ANOVA was performed on the thresholds (in dB, re 1 μ A) from the two-masker (M2) conditions, with factors of electrode spacing (2, 3, and 6), masker level (30, 50, and 70 % DR), and condition (MSK, ENH, and CON). There was a significant main effect of electrode spacing ($F_{1.6,74} = 19.2$, $P < 0.001$, partial $\eta^2 = 0.999$), masker level ($F_{1.3,60} = 201$, $P < 0.001$, partial $\eta^2 = 1.00$), and condition ($F_{1.8,84} = 288$, $P < 0.001$, partial $\eta^2 = 1.00$), as well as significant interactions between electrode spacing and masker level ($F_{3.7,169} = 7.05$, $P < 0.001$, partial $\eta^2 = 0.991$) and between electrode spacing and condition ($F_{3.1,142} = 11.0$, $P < 0.001$, partial $\eta^2 = 0.999$). Contrast analysis confirmed that there were significant differences between each of the three electrode spacings ($P < 0.05$ in all cases) and each of the masker levels and conditions ($P < 0.001$ in all cases).

A similar ANOVA was performed on the thresholds from the four-masker conditions, again with electrode

FIG. 2. Average thresholds (dB re 1 μ A) for each condition as a function of masker level for the simultaneous masking paradigm. Each panel represents a different combination of electrode spacing (Sp) and number of maskers (Mk). The THS and MAL values represent the average across all subjects on the target electrode 8. Error bars represent ± 1 standard error of the mean.

FIG. 3. Data from Figure 2 are replotted in terms of masked threshold relative to masker level (in dB) for each condition as a function of masker level for the simultaneous masking paradigm. The horizontal zero dB line represents the target level at which it is equal to the masker level, in terms of % DR. Error bars represent ± 1 standard error of the mean.

spacing, masker level, and condition as factors. There was a significant main effect for electrode spacing ($F_{1,47} = 10.3$, $P = 0.002$, partial $\eta^2 = 0.88$), masker level ($F_{1,4,66} = 156$, $P < 0.001$, partial $\eta^2 = 1.00$), and condition ($F_{2,93} = 194$, $P < 0.001$, partial $\eta^2 = 1.00$), as well as significant interactions between electrode spacing and masker level ($F_{1,9,87} = 5.06$, $P = 0.01$, partial $\eta^2 = 0.784$) and between electrode spacing and condition ($F_{2,93} = 4.88$, $P = 0.01$, partial $\eta^2 = 0.788$). Contrast analysis confirmed that there were significant differences between each of the masker levels and conditions ($P < 0.001$ in all cases).

To examine the effect of the number of maskers, thresholds in conditions with electrode spacings of 2 and 3 were analyzed. The four-way ANOVA confirmed significant main effects of electrode spacing ($F_{1,46} = 10.10$, $P = 0.003$, partial $\eta^2 = 0.88$), masker level ($F_{1,3,60} = 208$, $P < 0.001$, partial $\eta^2 = 1.00$), and condition ($F_{1,9,86} = 223$, $P < 0.001$, partial $\eta^2 = 1.00$), and revealed a main effect of number of maskers ($F_{1,46} = 111.14$, $P < 0.001$, partial $\eta^2 = 1.00$). There were significant two-way interactions between electrode spacing and masker level ($F_{1,9,87} = 5.07$, $P = 0.009$, partial $\eta^2 = 0.792$), electrode spacing and condition ($F_{1,9,88} = 8.53$, $P = 0.001$, partial $\eta^2 = 0.956$), number of maskers and condition ($F_{1,6,75} = 21.6$, $P < 0.001$, partial $\eta^2 = 1.00$), and masker level and condition ($F_{2,7,125} = 2.90$, $P = 0.043$, partial $\eta^2 = 0.649$). Significant three-way interactions were found between electrode spacing, number of maskers, and masker level ($F_{1,8,85} = 3.85$, $P = 0.028$, partial $\eta^2 = 0.660$), and between number of maskers,

masker level, and condition ($F_{3,4,158} = 3.12$, $P = 0.022$, partial $\eta^2 = 0.760$). Contrast analysis confirmed that there were significant differences between each of the three masker levels and conditions ($P < 0.001$ in all cases).

To calculate the amount of enhancement, according to the traditional method (EE_{sim1} in dB), we subtracted thresholds in the ENH condition from those in the MSK condition. The EE_{sim1} values for individual subjects, along with the averages across subjects, are shown in Figure 4. Each panel represents a different combination of electrode spacing and number of maskers, as in Figures 2 and 3.

A three-way (electrode spacing $\times$ number of maskers $\times$ masker level) ANOVA performed on the computed EE_{sim1} for the two-masker and four-masker conditions (electrode spacings 2 and 3 only) found a significant main effect of electrode spacing ($F_{1,7} = 7.28$, $P = 0.031$, partial $\eta^2 = 0.640$) and number of maskers ($F_{1,7} = 10.72$, $P = 0.014$, partial $\eta^2 = 0.801$), but not of masker level ($F_{1,1,7,8} = 0.861$, $P = 0.394$, partial $\eta^2 = 0.133$) or any interactions ($P > 0.100$ in all cases). The EE_{sim1} increased with increasing number of maskers (from 1.2 to 1.8 dB with Mk2, and from 1.8 to 2.6 dB with Mk4). Enhancement also increased with increasing electrode spacing (from 1.4 dB for Sp2 to 2.5 dB for Sp3 for the two-masker conditions and from 2.3 dB for Sp2 to 2.9 dB for Sp3 for the four-masker conditions at 70% DR).

In addition to the traditional definition of auditory enhancement, threshold differences between the

FIG. 4. Enhancement effect (EE_{sim1} in dB) for individuals as well as the mean data as a function of masker level for the simultaneous masking paradigm. Each panel represents a different combination of electrode spacing (Sp) and number of maskers (Mk).

ENH and CON conditions were also considered (EE_{sim2}). As can be seen in Figure 2, mean thresholds were always higher in the CON than in the MSK condition; therefore, the amount of enhancement (EE_{sim2}) was greater and averaged 5.5 dB. The EE_{sim1} and EE_{sim2} for masker level = 70 % DR are shown in Table 2. A two-tailed paired-samples t test confirmed a significant difference between EE_{sim1} ($M = 2.40$, $SD = 2.21$) and EE_{sim2} ($M = 5.49$, $SD = 2.48$) for the masker level of 70 % DR ($t_{78} = -5.89$, $P < 0.001$). One possible explanation for the increase in thresholds between the MSK and CON conditions is that the target component within the precursor generated some forward masking of the target component that followed. A three-way (electrode spacing $\times$ number of maskers $\times$ masker level) ANOVA performed on EE_{sim2} for the two-masker and four-masker conditions (electrode spacings 2 and 3 only) found a significant main effect number of maskers ($F_{1,7} = 7.41$, $P = 0.030$, partial $\eta^2 = 0.648$), but not of electrode spacing ($F_{1,7} = 4.40$, $P = 0.074$, partial $\eta^2 = 0.441$) or masker level ($F_{1,3,9,3} = 0.695$, $P = 0.466$, partial $\eta^2 = 0.123$). No interactions were significant ($P > 0.100$ in all cases).

Discussion

The results from experiment 1 provide strong evidence for auditory enhancement in CI users under simultaneous masking. The overall amount of enhancement (EE_{sim1}), averaged across subjects and conditions, was about 2.0 dB. Although this is not a large absolute

number, when taken as a proportion of the total dynamic range of CI users, it becomes more comparable to that found in normal-hearing listeners. Specifically, average enhancement as a proportion of overall dynamic range was about 12 %, which corresponds to about 12 dB, if we consider the dynamic range of normal-hearing listeners to be about 100 dB (Wang et al. 2015, 2016). This corresponds reasonably well to the maximum amount of enhancement reported in similar paradigms in normal-hearing listeners (Viemeister 1980).

Overall, the results suggest that auditory enhancement effects, as measured using simultaneous masking, are broadly comparable in normal-hearing listeners and CI users. This in turn provides further support for the conclusion that enhancement cannot be solely due to cochlear processes, or to efferent processes that project to the cochlea, such as the medial olivocochlear (MOC) reflex. The next experiment measures enhancement under forward masking to test whether CI users also exhibit similar levels of enhancement in that paradigm.

EXPERIMENT 2: MASKER ENHANCEMENT USING FORWARD MASKING

Methods

Seven of the eight subjects from experiment 1 took part in this experiment (subject D34 was unable to complete the experiment). The stimulus generation and presentation techniques were the same as those used in experiment 1. The precursor stimuli were again 500-ms

TABLE 2

Enhancement effects (EE, in dB) at a masker level of 70% DR for the simultaneous masking paradigm for different combinations of electrode spacing (Sp) and number of maskers (Mk)

Subject	Sp2/Mk2		Sp2/Mk4		Sp3/Mk2		Sp3/Mk4		Sp6/Mk2	
	EE_{sim1} (dB)	EE_{sim2} (dB)	EE_{sim1} (dB)	EE_{sim2} (dB)	EE_{sim1} (dB)	EE_{sim2} (dB)	EE_{sim1} (dB)	EE_{sim2} (dB)	EE_{sim1} (dB)	EE_{sim2} (dB)
D02	4.1	6.9	3.6	6.8	3.9	6.7	4.9	5.9	1.8	10.0
D19	1.5	4.5	3.4	6.0	3.3	8.6	1.9	7.8	1.9	8.3
D24	0.3	5.4	3.4	6.0	0.4	5.5	0.2	3.6	3.7	5.2
D27	-2.1	3.2	-0.7	4.7	-0.5	4.5	-0.7	3.0	2.7	6.8
D28	1.3	1.3	1.3	0.3	2.9	3.7	1.4	1.8	4.2	5.8
D33	3.8	4.2	0.2	1.1	5.1	4.0	10.1	7.4	2.3	9.1
D34	2.3	5.7	6.2	6.9	3.7	10.3	4.2	8.0	4.0	10.5
D36	0.3	4.0	1.0	3.3	1.5	5.1	1.3	3.1	1.8	4.5
Mean	1.4	4.4	2.3	4.4	2.5	6.1	2.9	5.1	2.8	7.5

EE_{sim1} is defined as the threshold in the MSK minus the threshold in the ENH condition. EE_{sim2} is defined as the threshold in the CON minus the threshold in the ENH condition

pulse trains, the masker stimuli were 100-ms pulse trains, and the probe was a 20-ms pulse train. All pulse trains again consisted of 32- μ s/phase, cathodic-first biphasic pulses, presented in the monopolar mode at a rate of 2000 pulses per second (pps). The gap durations between the precursor (when present) and the masker, and between the masker and probe were both 20 ms. A gap of 20 ms between the masker and the probe was deemed sufficient to reduce potential “confusion” effects that can occur between a masker and closely following probe (e.g., Neff 1986). Only one masker level (70 % DR) was tested here.

THS and MALs for the masker and probe stimuli were measured as in experiment 1. Threshold measurement procedures were also the same as in experiment 1. The different test conditions are shown in Figure 5. The MSK, ENH, and CON conditions are analogous to the conditions tested in experiment 1. The difference here is that the former “target” stimulus is now used as the masker for the new “probe” stimulus, to test for any enhancement of the masking effectiveness of the target component. The assumption of this experiment is that the masking of the probe is primarily due to the target component, rather than the neighboring masking components. In their original study, Viemeister and Bacon (1982) provided support for this assumption by showing that the masker components alone produced little forward masking. Because CI users’ spectral resolution is likely to be considerably poorer than that of normal-hearing listeners, we also tested this assumption directly by running two additional conditions. MSK0 and ENH0 conditions replicate the MSK and ENH conditions, but without the target component in the masker (see Fig. 5).

Results and Discussion

Figure 6 shows the average thresholds across the seven subjects in dB (re 1 μ A) for the different masker numbers

and spacing, with different symbols representing thresholds from the different precursor/masker configurations, as shown in the legend. The average unmasked THS and MAL for the brief probe on electrode 8 are shown by the solid and dotted lines, respectively. Considering the “classical” definition of enhancement (difference in thresholds between the MSK and ENH conditions, EE_{fwd1}), the CI users appear to show enhancement, as thresholds in the presence of the precursor (ENH) are higher than thresholds with no precursor (MSK). However, this interpretation is rendered less clear by the fact that the precursor with the target component included (CON) produces thresholds that are even higher than those in the ENH condition, so that the alternative measure of the enhancement effect (difference between the ENH and CON conditions, EE_{fwd2}) results in no (or indeed negative) enhancement. The higher threshold in the CON condition than in the ENH condition suggests that the increase in threshold between the MSK and ENH conditions may be due to the greater effects of a longer forward masker, rather than enhancement per se. The results from the MSK0 and ENH0 conditions support this interpretation: substantial forward masking of the probe was observed in the MSK0 condition, without the target component present, and the amount of masking increased substantially when the effective duration of the forward masker was increased by adding the precursor (ENH0), despite the fact that there was no target component to be enhanced.

Separate two-way ANOVAs were performed on the thresholds from the two-masker and four-masker configurations, with electrode spacing (2, 3, or 6) and condition as factors. For the two-masker configurations, there was a significant main effect of electrode spacing ($F_{2,80} = 48.3$, $P < 0.001$, partial $\eta^2 = 0.541$) and condition ($F_{1,9,77} = 103$, $P < 0.001$, partial $\eta^2 = 0.715$), as well as a significant interaction ($F_{5,3,217} = 10.2$, $P < 0.001$, partial $\eta^2 = 0.199$). Contrast analysis confirmed that there were significant differ-

FIG. 5. Schematic diagram of conditions tested under forward masking, where listeners must detect the presence of the brief probe (gray). In the MSK condition, no precursor is present. In the ENH condition, the precursor is present, which should lead to higher forward-masked thresholds, due to enhancement of the target (red). The CON condition has a precursor that includes the target

component. The MSK0 and ENH0 conditions are control conditions to test for the effect of masker duration where no enhancement effects are expected. Only the intervals containing the probe are shown.

ences between each of the three electrode spacings ($P < 0.001$ in all cases) and between each of the five conditions ($P < 0.05$ in all cases). For the four-masker configurations, there was a significant main effect of electrode spacing ($F_{1,41} = 55.2$, $P < 0.001$, partial $\eta^2 = 1.000$) and condition ($F_{1,9,80} = 84.1$, $P < 0.001$, partial $\eta^2 = 1.000$), as well as a significant interaction ($F_{3,6,149} = 2.48$, $P = 0.052$, partial $\eta^2 = 0.665$). Contrast analysis again confirmed that there were significant differences between each electrode spacing and each condition ($P < 0.01$).

To examine the effect of number of masker components, the thresholds for electrode spacings of 2 and 3 were analyzed. The three-way ANOVA confirmed a significant main effect of electrode spacing ($F_{1,41} = 42.3$, $P < 0.001$, partial $\eta^2 = 0.508$) and condition ($F_{1,7,70} = 103$, $P < 0.001$, partial $\eta^2 = 0.715$). The main effect of masker number was not significant ($F_{1,41} = 0.003$, $P = 0.954$, partial $\eta^2 = 0.000$), but there were significant interactions between electrode spacing and number of maskers ($F_{1,41} = 6.06$, $P = 0.018$, partial $\eta^2 = 0.129$), as well as between electrode spacing and condition ($F_{3,1,127} = 3.26$, $P = 0.023$, partial $\eta^2 = 0.074$). Contrast analyses again confirmed that there were significant differences between each condition ($P \leq 0.001$).

Figure 7 shows both the traditional (EE_{fwd1} ; left panel) and the newer (EE_{fwd2} ; middle panel) measures of enhancement, as well as the effects of masker duration (right panel), at both the individual and group levels. The measures confirm that, in contrast to the results using simultaneous masking (EE_{sim2}), no enhancement was observed under forward masking in CI users, when

FIG. 6. Average thresholds (dB re $1 \mu\text{A}$) for different combinations of electrode spacing (Sp) and number of maskers (Mk) under forward masking. The THS and MAL values represent the average across all subjects on the target electrode 8. Error bars represent ± 1 standard error of the mean.

FIG. 7. The amount of estimated enhancement (in dB), calculated in the traditional way (EE_{fwd1} ; left panel), and in a way that accounts for possible effects of masker duration (EE_{fwd2} ; middle panel). The right panel illustrates the effect of masker duration (DE_{masker}) for the two conditions (MSK0 and ENH0) that did not include a masker or precursor component at the target electrode.

the CON condition (precursor with the target component present) was taken as the reference condition (EE_{fwd2}). The large difference in thresholds between the MSK0 and ENH0 conditions also confirmed that the effects of masker duration seem to dominate the results, rather than anything related to enhancement.

DISCUSSION

Summary of Results

The aim of this study was to examine auditory enhancement in CI users with simultaneous and forward masking. The CI users exhibited enhancement in the case of simultaneous masking. By the traditional measure (target threshold without a precursor minus target threshold with a precursor, EE_{sim1}), the average amount of enhancement was about 2 dB. By another measure (difference in thresholds between precursors with and without the target component present, EE_{sim2}), the amount of enhancement was about 5 dB. Even the 2-dB enhancement effect was highly significant and represented about 12 % of the CI users' dynamic range, equivalent to about 12-dB enhancement in normal-hearing listeners (assuming a dynamic range of about 100 dB). In contrast, no clear enhancement was observed under forward masking. Although the traditional measure (EE_{fwd1}) indicated some enhancement, the other measure (EE_{fwd2}) showed no (or negative) enhancement, and the additional control conditions using maskers without the target component suggested that the apparent enhancement was probably due to the effects of increased masker duration, rather than enhancement per se.

Effects of Masker Level and Number and Spacing of Stimulated Electrodes

Under simultaneous masking, the amount of enhancement increased with increasing number of maskers, and with increasing electrode spacing between maskers (and between maskers and target), although the effects of level were not consistent. Some aspects of the results are qualitatively similar to that observed in normal-hearing listeners, and some are not. For instance, Viemeister (1980) observed less enhancement for a two- or three-component masker than for a four-component or broadband masker, just as less enhancement was observed here with the CI users for the two-component than for the four-component masker. On the other hand, Viemeister (1980) found that the amount of enhancement generally increased with increasing masker level from around 0 dB at 5 dB SPL per component masker level to around 10–15-dB enhancement at masker levels of 53 and 63 dB SPL, whereas the current study with CI users found no consistent effect of level between 30 and 70 % DR. Finally, Viemeister et al. (2013) found that enhancement was a nonmonotonic function of the masker's spectral notch width, reaching a maximum for notch widths of about 0.6 octaves. In our data, a small but significant increase in enhancement was observed as the masker electrode spacing increased from two to six electrodes. It is difficult to provide a precise comparison between spectral distance in acoustic hearing and electrode spacing in electric hearing, but in terms of frequency mapping, the two-electrode spacing corresponds to a spectral gap of about one octave, and the six-electrode spacing corresponds to a gap of about three octaves. The fact that enhance-

ment continued to increase over this wide range may be due to the much poorer spectral resolution of CI users (e.g., Henry et al. 2005; Anderson et al. 2012).

Differences Between Simultaneous and Forward Masking: Implications for Underlying Mechanisms

As outlined in the [Introduction](#), the presence of enhancement under simultaneous masking is consistent with both adaptation and adaptation-of-inhibition explanations of enhancement. In studies of normal-hearing listeners, a strong argument for the adaptation-of-inhibition hypothesis (Viemeister and Bacon 1982) is the effect of enhancement under forward masking, whereby the effectiveness of a forward masker is increased by the presence of a spectrally notched precursor. The lack of a clear enhancement effect under forward masking in CI users may therefore suggest differences underlying mechanisms. A similar lack of enhancement was reported by Thibodeau (1991) in listeners with sensorineural hearing loss: as with our CI users, the hearing-impaired listeners showed an increase in masking due to the precursor, but the increase was no greater than was found simply by increasing the duration of the masker itself.

A possible interpretation of this outcome is that both CI users and hearing-impaired listeners lack a specific mechanism that is present in normal-hearing listeners. One candidate for such a mechanism may involve the olivocochlear efferent system, which is bypassed by CIs and is reduced in effectiveness in hearing-impaired listeners, due to the loss of outer hair cell function (e.g., Guinan 2006) and/or lack of efferent activation (e.g., Berlin et al. 1993). Such a mechanism could potentially produce inhibition that adapts over time. However, direct tests of the role of the efferent system or other low-level contributors have not provided strong evidence so far (Carcagno et al. 2014; Beim et al. 2015).

Regardless of the underlying mechanisms, the results could be interpreted as meaning that CI users experience the adaptation required to observed enhancement under simultaneous masking, but not the adaptation of inhibition required to observe enhancement under forward masking. However, another type of explanation to explain some aspects of enhancement has invoked mechanisms of auditory perceptual organization. For instance, the precursor may be perceptually grouped with the masker, making the target “pop out” from the simultaneous masker (e.g., Carlyon 1989; Richards et al. 2004). Such effects are unlikely to rely on peripheral mechanisms, and so may remain intact in CI users and hearing-impaired listeners. Although these higher-level grouping and cueing mechanisms are unlikely to explain all

enhancement phenomena (Carcagno et al. 2013a; Feng and Oxenham 2015), they may help explain why some of the effects seem unaffected by hearing loss.

Finally, another possibility is that the difference between the forward-masking results of normal-hearing listeners and CI users lies not so much in differences in the underlying enhancement mechanisms, but in differences in spectral resolution that lead to stronger direct masking effects of the flanking electrodes (and stronger effects of masker duration in the control conditions) in forward masking in the CI users. Regardless of the underlying mechanisms, the fact that CI users experience abnormal effective enhancement, as measured in these experiments, suggests the possibility of perceptual consequences in real-world situations.

Overall, the results provide a complex pattern of results, whereby some aspects of enhancement remain intact through CIs but others do not. Auditory enhancement can be thought of as a byproduct of perceptual adaptation, which assists in detecting new sounds in an ongoing background, and which provides some degree of perceptual constancy in the face of varying acoustic backgrounds, different talkers, and different room environments. Any differences in these processes may help explain some of the challenges faced by CI users in complex acoustic backgrounds. Introducing signal processing to recreate any missing effects of enhancement in clinical populations (including CI users and hearing-impaired individuals) may provide some benefit in such situations.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of Interest The authors declare that they have no conflict of interest.

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