Research Article

Induced Loudness Reduction and Enhancement in Acoustic and Electric Hearing

NINGYUAN WANG,^{1,3} HEATHER KREFT,² AND ANDREW J. OXENHAM^{1,2}

¹*Department of Psychology, University of Minnesota, N218 Elliott Hall, 75 East River Rd., Minneapolis, MN 55455, USA*

²*Department of Otolaryngology, University of Minnesota, Rm 8-323 Phillips Wangensteen Building, 420 Delaware St. SE, Minneapolis, MN 55455, USA*

³*Nurotron Biotechnology Co., Ltd, Hangzhou, Zhejiang, China*

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ABSTRACT

The loudness of a tone can be reduced by preceding it with a more intense tone. This effect, known as induced loudness reduction (ILR), has been reported to last for several seconds. The underlying neural mechanisms are unknown. One possible contributor to the effect involves changes in cochlear gain via the medial olivocochlear (MOC) efferents. Since cochlear implants (CIs) bypass the cochlea, investigating whether and how CI users experience ILR should help provide a better understanding of the underlying mechanisms. In the present study, ILR was examined in both normal-hearing listeners and CI users by examining the effects of an intense precursor (50 or 500 ms) on the loudness of a 50-ms target, as judged by comparing it to a spectrally remote 50-ms comparison sound. The interstimulus interval (ISI) between the precursor and the target was varied between 10 and 1000 ms to estimate the time course of ILR. In general, the patterns of results from the CI users were similar to those found in the normal-hearing listeners. However, in the short-precursor short-ISI condition, an enhancement in the loudness of target was observed in CI subjects that was not present in the normal-hearing listeners, consistent with the effects of an additional attenuation present in the normal-hearing listeners but not in the CI users. The results suggest that the MOC may play a role but that it is not the only source of these loudness context effects.

Keywords: auditory context effects, loudness, loudness recalibration, cochlear implants

INTRODUCTION

As with many other aspects of perception, the loudness of a sound depends not only on its physical properties but also on the context in which the sound is presented. One loudness context effect that received early attention was termed “loudness enhancement.” This effect was demonstrated by presenting three successive tones at the same frequency: a precursor, a target tone, and a comparison tone. Listeners were instructed to adjust the level of the comparison tone until its loudness matched that of the target. When the precursor was more intense than the target, the listeners often adjusted the level of the comparison tone to be higher than that of the target at equal loudness, leading to the conclusion that the precursor had enhanced the loudness of the target tone (Zwislocki and Sokolich 1974; Elmasian and Galambos 1975). These effects declined as the spectral distance between the precursor and the target increased and tended to disappear completely at large spectral distances (Marks 1994; Wang et al. 2015).

The effects of loudness recalibration (LR; e.g., Ariele and Marks 2003) or induced loudness reduction (ILR; e.g., Nieder et al. 2003) are also measured by using a precursor at the same frequency as the target, but the comparison tone is at a frequency remote from that of the target and precursor. Using this paradigm, the opposite effect is usually reported: a precursor that is

Correspondence to: Ningyuan Wang · Nurotron Biotechnology Co., Ltd · Hangzhou, Zhejiang, China. email: wang2087@umn.edu

more intense than the subsequent target tone can reduce the target's loudness (Marks 1994). Mapes-Riordan and Yost (1999) found that the effect was strongest when the precursor was 10–20 dB higher than the target and that the effect was smaller or non-existent when the level difference exceeded 40 dB or when the target was presented at or near its detection threshold.

Scharf et al. (2002) suggested that the results from earlier loudness enhancement studies should be reinterpreted in light of the ILR findings. They noted that when all three tones were presented at the same frequency (as in the traditional enhancement studies), the precursor may have reduced the loudness of the comparison tone rather than enhancing the loudness of the target tone. This reinterpretation was supported by Ariei and Marks (2003), who found that ILR did not occur immediately after a precursor, but reached a maximum at a delay of around 1 s, and lasted for at least 3 s (Ariei and Marks 2003), which was longer than the gaps between precursor and comparison in the previous loudness enhancement studies.

To further test this interpretation, Oberfeld (2007) measured loudness context effects with the traditional three-tone paradigm where all tones were presented at the same frequency, along with a novel four-tone paradigm, in which a fourth tone was presented at a different frequency to measure more directly the perceived loudness of the third (comparison) tone. Results from Oberfeld (2007) showed that not only was the target tone enhanced in loudness, but the loudness of the comparison was reduced, in line with a “dual-process” model proposed by Ariei and Marks (2003). In this model, a fast-onset and fast-decay “enhancement” process, accompanied by a fast-onset and slow-decay reduction process, contribute to the “loudness enhancement” of the target.

One way in which the rapid enhancement process could occur is through “assimilation” or “over-integration” of the loudness of the precursor with that of the target (Plack 1996). This is thought to occur only when the precursor and target are perceptually similar (Oberfeld 2008). Some evidence in favor of the assimilation hypothesis is that a decrement in the judged loudness of the target can occur when the precursor is lower in level than the target (Elmasian et al. 1980). In addition, the assimilation hypothesis can explain why enhancement is sometimes observed even when the enhancer follows the target in time (Elmasian et al. 1980). One potential mechanism of ILR involves the medial olivocochlear (MOC) efferent system (e.g., Nieder et al. 2003), which can reduce cochlear gain by controlling the action of the outer hair cells (Stankovic and Guinan 1999; Guinan 2006). This in turn reduces neural firing and could reduce loudness. Although the time constants associated with the MOC fast effect are not thought to extend to several seconds, the MOC slow

effect may potentially contribute to loudness changes (Cooper and Guinan 2003).

Cochlear implants (CI) may provide a way to examine the role of the MOC efferents in ILR. If the MOC system is the sole source of ILR, then ILR should not be observed in CI users. A recent study by Wang et al. (2015) investigated loudness context effects in CI users using the traditional three-stimulus technique, with all three stimuli presented to the same electrode. Wang et al. (2015) found both similarities and differences between the results from CI users and those from normal-hearing listeners. In particular, in both normal-hearing and CI groups, a more intense precursor resulted in the target sound being judged louder than the comparison signal when they were presented at equal levels, and frequency selectivity was observed in this effect. In contrast, an increase in precursor level led to an increase in the effect for the normal-hearing listeners but not for the CI users. Because the target and the comparison tone were presented to the same electrode, it was not possible to separate potential loudness enhancement from ILR effects.

In the present study, we measured ILR in both normal-hearing listeners and CI users, with a moderately intense precursor and a fixed-level target, presented at the same frequency (or same electrode), and a varying-level comparison, presented at a spectrally remote frequency (or electrode) from the precursor and the target. Listeners were asked to compare the loudness of the comparison with that of the target. Pure tones were used as stimuli for the normal-hearing listeners, whereas fixed-rate electrical pulse trains were presented directly to the CI users. Our targets were always 50 ms in duration. The precursor duration was either 50 or 500 ms. If enhancement is due to a higher-level assimilation process, then both normal-hearing listeners and CI users should exhibit the effect, which should be maximal when the precursor and target are of similar duration (and therefore are most perceptually similar). If ILR is governed by the MOC system, it should be present only for the normal-hearing listeners, and should be greater for longer-duration precursor, which allows for more build-up of the MOC effect (Guinan 2006).

METHODS

Subjects

Normal-Hearing Listeners

Ten listeners (3 males, 7 females) participated in this experiment and were compensated for their time. Their ages ranged from 19 to 63 years (mean age 25.3 years, with only one subject older than 45). All

listeners had audiometric thresholds below 20 dB HL at octave frequencies between 0.25 and 8 kHz.

Cochlear-Implant Users

Seven post-lingually deafened CI users participated in this study and were compensated for their time. Their ages ranged from 54.1 to 74.4 years (mean age 62.0 years). Information regarding the individual CI users is provided in Table 1.

Stimuli

Normal-Hearing Listeners

Figure 1 provides a schematic diagram of the stimuli used in this experiment. In each trial, three pure tones, a precursor at 1278 Hz, a target also at 1278 Hz, and a comparison at 455 Hz, were presented in sequence. The spectral distance between the precursor and comparison was selected to be large enough to avoid any effects of the precursor on the comparison (e.g., Marks 1994). The frequencies of the test tones were selected from the standard Advanced Bionics 16-channel map for CIs, corresponding to the center frequencies of the channels mapped to electrodes E8 and E2, respectively. For reasons outlined in the introduction, two precursor durations, 50 and 500 ms, were tested. The durations of both the target and the comparison were always 50 ms. All the stimuli were gated on and off with 10-ms raised-cosine ramps. The interstimulus interval (ISI) between the precursor and the target was 50, 250, or 1000 ms, and the ISI from the target to the comparison was fixed at 1000 ms. The six precursor conditions (two durations and three ISIs) were tested along with a reference

FIG. 1. Schematic diagram of the stimuli used for both the normal-hearing listeners and CI users. For the normal-hearing listeners, the precursor was a pure tone at 1278 Hz and 75 dB SPL, presented for either 50 or 500 ms. A 50-ms target tone at the same frequency and 60 dB SPL followed it after a gap of 50, 250, or 1000 ms. After a further 1000-ms gap, a 50-ms comparison tone with adjustable level was presented at 455 Hz. For the CI users, the stimuli had the same overall durations, but were presented as pulse trains to different electrodes. The precursor and target were presented to a middle electrode (E8), whereas the comparison was presented to a more apical electrode (E2). The level of the precursor was set to the most comfortable level (MCL) and the target was set to 70 % of each subject's dynamic range.

condition with no precursor, giving a total of seven conditions. The levels of the precursor (when present) and the target were always 75 and 60 dB SPL, respectively. The level of comparison tone was modified according to subjects' responses in an adaptive procedure, described below. The stimuli were generated digitally and played out diotically from a LynxStudio L22 24-bit soundcard at a sampling rate of 48 kHz via Sennheiser HD650 headphones to listeners seated in a double-walled sound-attenuating chamber.

TABLE 1

Subject code	Gender	Age (years)	CI user information				
			CI use (years)	Etiology	Duration of hearing loss prior to implant (years)	Absolute threshold (μ A)	MCL (μ A)
D02 (☆)	F	63.9	12.1	Unknown	1	73	356
D10 (◇)	F	59.4	10.8	Unknown	8	68	509
D19 (□)	F	54.1	9.4	Unknown	11	86	475
D24 (△)	M	63.3	5.9	Unknown	27	91	413
D28 (●)	F	64.6	10.6	progressive Familial	27	186	766
D33 (▽)	M	74.4	1.0	progressive SNHL	<1	55	637
D36 (○)	F	54.5	1.5	Noise exposure; trauma	Unknown	173	863
				High fever			

MCL denotes maximum comfortable loudness

Cochlear-Implant Users

The stimuli were similar to those used for normal-hearing listeners (Fig. 1). All the stimuli were delivered directly to the Internal Cochlear Stimulator (ICS) system based on a clinical research platform, BEDCS, provided by Advanced Bionics (Valencia, CA). The durations of all the signals and gaps were the same as those used with the normal-hearing listeners, with the exception that no onset and offset ramps were used. The stimuli were all pulse trains, consisting of 32 μ s/phase, cathodic-first biphasic pulses, presented in monopolar mode at a rate of 2000 pulses per second (pps). Electrode 8 was selected to present the precursor and target, and the comparison was presented from electrode 2. These electrodes correspond to frequencies of 1278 and 455 Hz, respectively, according to the standard Advanced Bionics 16-channel map. Presentation levels were determined for each subject individually by setting the target level at 70 % of the dynamic range (DR), defined as the range from absolute threshold (THS) to most comfortable level (MCL) in microamperes (μ A), and by setting the precursor level at MCL. The level of the comparison stimulus was varied using the same adaptive procedure as for the normal-hearing listeners in units of percent in DR.

Procedure

Normal-Hearing Listeners

Listeners were instructed to ignore the first stimulus, the precursor (if present), and to judge whether the comparison was louder or quieter than the target. An interleaved tracking procedure (Jesteadt 1980), consisting of a two-down one-up track and a two-up one-down track, was employed to estimate to the point of subjective equality (PSE) in loudness between the target and comparison tones. The two adaptive procedures track the 70.7 and 29.3 % points on the psychometric function, so that the mean of the two tracks approximates the 50 % point on the psychometric function, i.e., the point at which the target and comparison were judged to be equally loud. Each trial was selected at random with equal priori probability from one of the two tracks. Each condition was repeated four times in random order, with a different random order selected for each subject and each repetition. However, for each repetition, a different pair of starting points was selected for the tracking procedure (51/60, 54/63, 57/66, and 60/69 dB SPL), to reduce and control for any potential response bias generated by the starting points (e.g., Marks 1994). In each track, the initial step size was 5 dB. The step size was reduced to 3 dB after the first two reversals, and to 2 dB after the fourth reversal. A block of trials ended

when four reversals at the final step size occurred in both tracks. If the stopping rule for one track was met before the other, the “completed” track would continue, but the levels were not incorporated into the PSE estimates. The final measured PSE (i.e., the level at which the comparison was judged louder than the target 50 % of the time) was the mean of the last four reversal points from both tracks. The seven conditions with four starting values resulted in a total of 28 runs per subject.

Cochlear-Implant Users

The experimental procedures for the CI users were the same as those used for the normal-hearing listeners, with the following exceptions. First, the THS and MCL levels were determined for each subject individually using 200-ms pulse trains on each of the test electrodes (E2 and E8), as described in Wang et al. (2015). Second, the different pairs of starting points for each of the four repetitions of the adaptive tracking procedure were 55/70, 60/75, 65/80, and 70/85 % DR. Third, the initial step size in the adaptive procedure was 5 % DR, which was reduced to 3 % DR after two reversals and to 2 % DR after four reversals.

RESULTS

Normal-Hearing Listeners

A one-way within-subjects ANOVA revealed no significant main effect of starting point in the adaptive procedure [$F(3,27)=1.13$, $p=0.353$], suggesting that the starting points did not affect the actual matches of subjects. Therefore, the results were averaged across the four runs with different starting points for the remainder of the analysis. The mean results are presented in the left panel of Figure 2. The black bar at the left represents the results from the baseline condition with no precursor. The mean level of the 455-Hz comparison tone was 58.3 dB SPL, which was not significantly lower than the 60-dB SPL of the 1278-Hz target tone [paired-samples t test: $t(9)=-1.08$, $p=0.307$]. The lack of a level difference is expected, given the relatively similar expected loudness of 455-Hz and 1278-Hz tones, based on the 60-phon curve from current iso-loudness contours (ISO:226 2003). The presence of the precursor generally reduced the level of the comparison tone at the PSE, indicating a reduction in the loudness of the target tone, as expected. The right panel of Figure 2 displays the amount of loudness reduction, calculated simply by subtracting the level of the comparison in the presence of the precursor from its level in the absence of the precursor. The maximum ILR of about 7 dB

FIG. 2. Mean results from normal-hearing listeners. In the left panel, from left to right, the matched levels of comparison tone in no-precursor (baseline), short-precursor (50 ms), and long-precursor (500 ms) conditions are displayed. In the right panel, the levels in each condition are shown, relative to baseline. The

filled and open circles represent results from conditions with the 50-ms and 500-ms precursor, respectively. The dashed line indicates the baseline. Error bars represent 1 s.e. of the mean across subjects.

was found for ISIs of 1 s for both the 50-ms and the 500-ms precursor. At shorter ISIs, the longer precursor continued to produce ILR, whereas the amount of ILR produced by the shorter (50-ms) precursor decreased with decreasing ISI, reaching an average of less than 1 dB at the shortest ISI of 50 ms.

The increase in ILR with increasing ISI out to 1 s is consistent with the results from previous studies (Arieh and Marks 2003; Nieder et al. 2003). The maximum effect of 7 dB is somewhat less than that reported in earlier studies (around 10 dB), although this may be due to the relatively small level difference we used between the 60-dB target and the 75-dB precursor. Most previous studies have used precursor levels of 80 dB SPL, with level differences between the precursor and target of 20 dB or more. The amount of ILR has generally been found to reach a maximum with a level difference of around 20–30 dB between the precursor and target (Mapes-Riordan and Yost 1999; Oberfeld 2007). A two-way within-subjects ANOVA was conducted, with the change in level (relative to the no-precursor condition) as the dependent variable and precursor duration and ISI as the two factors. A significant main effect was found for precursor duration [$F(1,9)=9.59$, $p=0.013$], in line with the observation that the longer precursor induced a larger effect overall. The main effect of ISI was also significant [$F(2,18)=16.38$, $p<0.001$], as was the interaction between precursor duration and ISI [$F(2,18)=4.74$, $p=0.022$], reflecting the observation that the effect of precursor duration was greatest at the smallest ISI and became much smaller at the longest ISI.

According to the two-component model of Arieh and Marks (2003), the effects of a precursor are a combination of a short-lived enhancement process, which lasts no more than about 100 ms, superimposed on a longer-lasting ILR, which reaches a maximum after about 1 s. If we assume that only ILR remains at an ISI of 1 s, then the magnitude of the enhancement

component can be defined as the difference between the level of the comparison in the 1000-ms ISI condition and its level at shorter ISIs as suggested in Oberfeld (2007). According to this approach, the maximum ILR is about 7 dB for both the 50-ms and 500-ms precursors, and the maximum amount of enhancement (observed at an ISI of 50 ms) is about 6 dB for the 50-ms precursor and 3 dB for the 500-ms precursor. Thus, for the normal-hearing listeners, the prediction of greater enhancement for the shorter precursor was confirmed; however, the prediction of greater ILR for the longer precursor was not supported.

Cochlear-Implant Users

The individual matched levels of the comparison tone were converted into dB re. 1 μ A and were then averaged. As in experiment 1, a one-way within-subjects ANOVA revealed no significant difference in the response level with different starting points of the adaptive tracking procedure [$F(3,18)=1.46$, $p=0.26$], so the results were averaged across the four different starting levels.

The mean results from CI users are shown in Figure 3. In the left panel, the baseline condition with no precursor is shown with the black bar. It is not informative to compare the current levels of the comparison and target in the baseline condition, as they were presented to different electrodes, and so likely have different loudness-level relationships. In general, the effects of the precursor seem greater for the 50-ms precursor than for the 500-ms precursor. There was a trend for a decreasing PSE with an increasing ISI for the 50-ms precursor, but the trend was less apparent for the 500-ms precursor. The effect of the precursor was again calculated by subtracting the comparison level at the PSE in the no-precursor condition from the comparison level at the PSE in the with-precursor conditions (right panel of Fig. 3). In

FIG. 3. Mean results from CI users. In the *left panel*, the individual matched levels of comparison tone were converted into decibel re. 1 μ A, and averaged to the mean matched levels. From left to right, the matched levels of comparison tone in no-precursor (baseline), short-precursor (50 ms), and long- precursor (500 ms) conditions are displayed. In the *right*

panel, the levels in each condition are shown, relative to baseline. The *filled and open circles* represent results from conditions with the 50-ms and 500-ms precursor, respectively. The *dashed line* indicates the baseline. Error bars represent 1 s.e. of the mean across subjects.

one case (50-ms precursor and 50-ms ISI), the comparison level was higher in the presence of the precursor. In all other cases, the mean PSE with the precursor were the same as, or lower than, the levels without the precursor, as was also found for the normal-hearing listeners under all conditions.

A two-way within-subjects ANOVA was performed with the change in level (in dB, relative to the no-precursor condition) as the dependent variable, and precursor duration and ISI as the two factors. A significant main effect was obtained for precursor duration [$F(1,6)=12.3$, $p=0.013$]. The main effect of ISI failed to reach significance [$F(2,12)=3.52$, $p=0.063$], but the interaction was significant [$F(2,12)=4.71$, $p=0.031$], reflecting the greater effect of ISI for the 50-ms precursor than for the 500-ms precursor.

Comparison of Results from Normal-Hearing and Cochlear-Implant Subjects

When considered in isolation, the patterns of results from the CI group with each of the two precursors look reasonably similar to those found in the normal-hearing subjects: with the 50-ms precursor, the matched comparison level decreased with increasing ISI, and with the 500-ms precursor the effect of ISI was reduced. However, when comparing the absolute effects of the presence of the precursor, some differences between the data from the CI users and the normal-hearing subjects emerge. As shown in the right panel of Figure 3, the mean difference between the precursor and no-precursor PSE levels is positive for the 50-ms precursor and 50-ms ISI, implying that the enhancement effect was greater than the ILR for the CI users. In contrast, as shown in the right panel of Figure 2, the normal-hearing listeners showed no overall enhancement in any of the conditions tested.

A more direct or quantitative comparison of the data from the normal-hearing and CI groups is

hampered by the differences in overall dynamic range, and by uncertainty regarding the appropriate units in which to compare the data. One way to provide such a comparison is to convert the amount of change in the matching stimulus into a proportion of the overall dynamic range (Wang et al. 2015). We calculated these normalized values by considering the dynamic range of the CI users to be the difference between MCL and THS (in dB) for each subject individually, and then converting any changes in level into a proportion of the dynamic range. For instance, if the overall dynamic range was 10 dB, then a change in the comparison level of 1 dB was considered a 10 % change. For the normal-hearing listeners, the total dynamic range was assumed to be 100 dB. Using these conversions, the individual normalized effects of the precursors are shown in Figure 4, with the normal-hearing listeners on the left and the CI users on the right.

For the normal-hearing listeners, only 3 out of 10 subjects showed a positive overall effect of the precursor, and the average proportion of level change is slightly below the baseline as shown in Figure 2. In other conditions, the overall effect is even more clearly negative, indicating that ILR dominated any potential enhancement effects. In contrast, for the CI users in the 50-ms ISI and 50-ms precursor condition, six out of seven subjects showed more enhancement than ILR, resulting in a significant overall enhancement effect, as confirmed by a one-sample t test between the normalized level change and 0 % [$t(6)=2.85$, $p=0.029$]. In the 50-ms ISI and 500-ms precursor condition, more inter-subject variability was observed, with no clear trend for overall enhancement.

Despite the slightly different number of subjects in each group (7 vs. 10), a mixed-model ANOVA using type-III sums of squares (Keppel and Wickens 2004) on the normalized proportion of level change with group (normal-hearing or CI) as a between-subjects

FIG. 4. Individual normalized proportion of level change in normal-hearing listeners and CI users. In the *left panel*, *black, gray, and unfilled arrows* indicate results from 50, 250, and 1000-ms ISI conditions, respectively. Each symbol represents the normalized effect of precursor of an individual subject. The *black lines* indicate

the mean results of each condition. The *triangles* (NH63) indicate the results of the oldest (63-year-old) NH subject. The *right panel* shows individual results of CI users. The corresponding symbols of CI users are indicated in Table 1. The *dashed line* indicates the baseline.

factor, and ISI and precursor duration as two within-subjects factors revealed a significant effect of group [$F(1,15)=4.69$; $p=0.047$], a significant effect of ISI [$F(2,30)=14.6$; $p<0.001$], and a significant effect of precursor duration [$F(1,15)=23.7$; $p<0.001$]. A significant interaction between ISI and precursor duration was also found [$F(2,30)=9.24$; $p=0.001$], whereas no significant interactions with subject group were found. The main effect of group, and lack of significant interactions with group, support the observation that the effect of the precursors in the CI group was vertically shifted up relative to the effect found in normal-hearing listeners.

DISCUSSION

In the present study, we investigated potential interactions between ILR and enhancement in both normal-hearing listeners and CI users. When considering the two precursor conditions in isolation, the patterns of results from the CI users look reasonably similar to those found in the normal-hearing listeners: with the 50-ms precursor, the matched comparison level decreased with increasing ISI, and with the 500-ms precursor the effect of ISI was reduced. However, when comparing the results with and without a precursor, some differences between the results from the CI users and the normal-hearing subjects emerge. For the CI users, in the 50-ms precursor and 50-ms ISI condition, the mean difference between the precursor and no-precursor PSE levels was positive, implying more enhancement than ILR. In contrast, there were no conditions with the normal-hearing listeners that showed an overall enhancement in the loudness of the target.

The ability to distinguish between an enhancement of the loudness of the target and a reduction in the loudness of the comparison is only possible through the use of a different frequency (or electrode) for the comparison. The assumption is that any effects of the precursor will be frequency selective, and so will not extend to the frequency of the comparison stimulus. This assumption is generally well supported by the work of Marks and colleagues, who have shown that the effects of ILR, or loudness recalibration, are highly frequency selective and are reduced or absent once the two frequencies differ by more than about 15 %, or a “critical band” (e.g., Marks 1994). It is known that CI users generally exhibit much poorer frequency selectivity than normal-hearing listeners (e.g., Zeng 2004). An earlier study of spectral enhancement of vowels (Wang et al. 2012) found that CI users showed generally less enhancement than normal-hearing listeners, but that the difference was reduced once poorer spectral resolution was simulated in normal-hearing listeners using vocoder techniques. It is therefore possible that the differences observed in the present study between normal-hearing listeners and CI users may be due to the CI users’ poorer spectral resolution. This explanation seems unlikely to account for the whole effect, however, given the earlier results of Wang et al. (2015). They found that loudness context effects in CI users decreased with increasing electrode distance between the precursor and target, and were generally negligible when the precursor was presented to electrode 8 and the target was presented to electrode 2. Thus, the reduction in spectral resolution in CI users is unlikely to account fully for the differences in ILR observed here.

Another difference between normal-hearing listeners and CI users is the presence of the MOC

efferent system in the normal auditory system (e.g., Liberman 1988; Stankovic and Guinan 1999). The amount of enhancement (defined as the difference in comparison level between the 50- and 500-ms ISI with the 50-ms precursor) was very similar for both the normal-hearing listeners and the CI users—in both cases it amounted to about 6 % of the respective dynamic range on average. However, the CI results suggest less reduction in initial gain, relative to the normal-hearing listeners, leading to somewhat less ILR at the longest ISI. It is possible that the gain reduction “missing” from the CI data may reflect the absence of the MOC-induced gain reduction, which in this case led to some initial overall loudness enhancement for the CI users. However, the fact that ILR was observed at all in CI users is consistent with previous findings suggesting that loudness context effects (Wang et al. 2015) as well as auditory enhancement effects (Goupell and Mostardi 2012; Wang et al. 2012) cannot be mediated solely by the MOC efferent system. An alternative candidate is neural adaptation, which occurs at many levels of the auditory system, beginning in the auditory nerve (Pickles 2013).

A final consideration is the potential effect of age. Our CI users were on average considerably older than our normal-hearing listeners. Any MOC effects may decrease with age (Kim et al. 2002; Jacobson et al. 2003). However, as shown by the triangles in the left panel of Figure 4, our oldest normal-hearing listener (NH63) performed very similarly to the younger normal-hearing listeners. Thus, although we cannot rule out the possibility that age differences affected our results, it does not appear to have played a critical role.

In summary, the predictions outlined in the introduction were partially supported. Both normal-hearing listeners and CI users exhibited similar amounts of enhancement (defined as the difference in the comparison level between the 50- and 1000-ms ISI with a 50-ms precursor), consistent with expectations of a centrally located assimilation effect. The effect of ILR (defined as the difference in comparison level between the condition without a precursor and the condition with a precursor separated by a 1000-ms ISI) was somewhat reduced, but not eliminated, in the CI users; in addition, ILR was not greater with the 500-ms precursor than with the 50-ms precursor. Neither of these findings is consistent with predictions based on a completely peripheral (i.e., MOC) locus for ILR. However, the fact that ILR was somewhat reduced in the CI users suggests that peripheral processes may contribute to the overall effect.

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