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Changing stimulation patterns can change the broadness of contralateral masking functions for bilateral cochlear implant users

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Abstract

Past studies have found that contralateral masking functions are sharper than ipsilateral masking functions for cochlear implant (CI) users. This could suggest that contralateral masking effects are only sensitive to the peak of the masker stimulation for this population. To determine if that is the case, this study investigated whether using broader stimulation patterns affects the broadness of the contralateral masking function. Contralateral masking functions were measured for six bilateral CI users using both a broad and narrow masker. Results revealed that the broad masker resulted in a broader contralateral masking function. This would suggest that stimulation outside of the peak of the masker affects contralateral masking functions for CI users.

Graphical abstract

Keywords

Contralateral masking; bilateral cochlear implants

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2. Introduction

Auditory masking reflects the increase in the detection threshold of a probe signal in the presence of a masking signal. Masking can occur both within ear (ipsilateral masking) and across ears (contralateral masking). While ipsilateral masking for normal hearing (NH) listeners is thought to largely reflect peripheral mechanisms such as suppression of the basilar membrane mechanics (Plack and Oxenham, 1998; Wegel and Lane, 1924), contralateral masking is thought to reflect the activation of the contralateral efferent medial olivocochlear (MOC) pathway (Puria et al., 1996; Warren and Liberman, 1989; Zwislocki, 1971). The contralateral efferent MOC pathway directly innervates the outer hair cells (OHC) in the cochlea and, when activated, suppresses the OHC activity. This in turn reduces inner hair cell activation in the contralateral (probe) ear, thus elevating thresholds at the cochlea (Collet et al., 1994; Liberman and Brown, 1986; Smith and Keil, 2015; Warr and Guinan, 1979).

However, contralateral masking has also been found with cochlear implant (CI) users (Aronoff et al., 2015; James et al., 2001; Lin et al., 2013; van Hoesel and Clark, 1997), where the MOC pathway is unlikely to affect perception, given the direct stimulation of the auditory nerve by the cochlear implant. This suggests that an interaction between the bilateral signals may be taking place within the central auditory system in this population. There is evidence that some effects associated with contralateral masking are different in the two populations, consistent with different underlying mechanisms. For example, unlike with NH listeners (Dirks and Malmquist, 1965; Hughes, 1940; Ingham, 1957; Mills et al., 1996; Zwislocki, 1971; Zwislocki et al., 1968), for CI users there is no change in masked thresholds with changes to the masker intensity and onset delay (Lin et al., 2013). Similarly, while the magnitude of contralateral masking is dramatically smaller than that of ipsilateral masking for NH listeners (Mills et al., 1996; Zwislocki et al., 1968), the magnitude of contralateral and ipsilateral masking can be similar in CI users (Aronoff et al., 2015).

There are also some similarities between CI users' and NH listeners' contralateral masking functions. One such characteristic is that contralateral masking functions are sharper than ipsilateral masking functions (Aronoff et al., 2015; Mills et al., 1996). The underlying mechanism for this sharpening is unclear. It may indicate that the contralateral masking effect reflects only the influence of the peak of the masker. This is particularly important for CI users where techniques are being developed that manipulate the spread of the electrical field using multi-electrode stimulation (Berenstein et al., 2008; Bierer and Middlebrooks, 2002; Jolly et al., 1996; Landsberger et al., 2012; Landsberger and Srinivasan, 2009; Spelman et al., 1995; Srinivasan et al., 2010; Wu and Luo, 2014). If stimulation away from the peak affects contralateral masking patterns, this could suggest that multi-electrode stimulation techniques could also affect how signals interact within the central auditory system. The goal of this study is to determine whether the peak of the masker alone affects masking functions for CI users. To do that, contralateral masking functions were measured utilizing maskers that varied in broadness.

3. Methods

Subjects

Six bilaterally implanted subjects participated in this study. All participants had Advanced Bionics CII or HiRes 90k implants. All subjects were experienced bilateral CI users, ranging from 2 to 14 years of bilateral CI experience. Further subject details are provided in Table 1.

Apparatus

The experiment was conducted using the Bionic Ear Data Collection System (BEDCS v1.18, Advanced Bionics, Valencia, CA), which was controlled by custom Matlab software. Stimulation in each ear was controlled by separate computers. Each implant was directly controlled and connected via a Platinum Series Processor (PSP) connected to a clinicians programming interface (CPI).

Stimuli

Stimulation parameters—Electric pulses had a phase duration of approximately 32 μ s and a pulse rate of 1000 pulses per second. These are within the range of stimulation parameters used within a typical clinical setting.

Probe Signal—The probe stimulation delivered to current-steered locations in the left implant was a 20 msec monopolar anodic leading biphasic pulse train. Current steering was used by stimulating two adjacent electrodes, simultaneously and in phase, creating a virtual channel with an electrical field centered at a region in between the physical locations of the stimulated electrodes (Firszt et al., 2007). By manipulating the relative amount of current on each of the two stimulating electrodes, virtual channels could be created at any point between the two physical electrodes. Without utilizing virtual channels, the masking functions would be limited to probes with a minimal spacing of one whole electrode, which may provide insufficient accuracy to measure the peak of the sharp contralateral masking functions seen for CI users (Aronoff et al., 2015). The probe signal was presented at periodic intervals with 5 msec jitter to minimize subjects' ability to anticipate the probe timing.

Contralateral Masker—The masker stimulation was delivered to the right CI. Two masker conditions were utilized. The *narrow masker* condition consisted of monopolar anodic leading biphasic pulse stimulation at electrode location 8. The *broad masker* condition consisted of the same stimulation of electrode location 8 (center electrode), with the same stimulation intensity as the narrow masker condition, while simultaneously stimulating both electrode 7 and electrode 9 in phase at 10% of the intensity of electrode 8 (i.e., the center electrode) (Figure 1). Electrodes 7 and 9 will be referred to here as flanking electrodes, not to be confused with the term flanking bands used in acoustical comodulation masking release studies. The intensity magnitude of 10% of the center electrode was chosen for the flanking electrodes because pilot data indicated that it resulted in a clearly detectable increase in loudness, but also allowed for the stimulation level for both maskers to be audible. The stimulation level for the center electrode for both masking conditions were set so that the narrow masker was at a comfortable or soft but comfortable loudness level while the broad masker, with the additional flanking electrode stimulation, was not uncomfortably

loud. The electrode location for the masker was chosen to be at the center of the 16 electrode implanted array to minimize the likelihood of contralateral masking peaks beyond the extent of the implanted array.

Since the broad masker used the same stimulation intensity at electrode 8 as the narrow masker, but with additional current from in-phase stimulation of the flanking electrodes, the current level was initially determined for the broad masker at a loud but comfortable level to minimize the risk of presenting uncomfortably loud sounds. All participants reported hearing the narrow masker and it was typically described as being at either a comfortable or a soft but comfortable level.

Procedures

Prior to measuring masking functions, the maximum acceptable loudness level was identified for each electrode. The testing software prevented any single electrode stimulation above that level. Electrodes that were disabled in the subjects' clinical programs were not stimulated.

Unmasked Thresholds—Unmasked thresholds (Figure 2) were obtained with the probe signal using a modified Bekesy approach (e.g., Aronoff et al., 2015). Subjects were instructed to press and hold the space bar on a keyboard when they heard a sound. The stimulus was presented while a box turned yellow on a display monitor. The subject was instructed to release the space bar when the box was yellow but no sound was heard (i.e., stimulation was below threshold). Each tracking sequence consisted of 10 reversals (5 ascending and 5 descending) where the step size for the first four reversals was 1 dB and the step size for the final six reversals was 0.5 dB, in terms of stimulation level (μA). For the initial descending tracking sequence, the stimulation level started above threshold to ensure audibility. The probe amplitude decreased by 1 step size for every trial until the subject released the space bar, which indicated that the probe signal was no longer audible. The probe amplitude was then decreased by 2 step sizes ensuring inaudibility and then the ascending tracking sequence began where the stimulation level increased by 1 step size until the subject indicated audibility by again pressing and holding down the space bar. Once the subject indicated that the sound was audible again by pressing down the space bar, the probe amplitude was increased by 2 step sizes to ensure audibility and the descending tracking sequence continued. Thresholds were calculated as the 20% trimmed mean of the final six sequences. The 20% trimmed mean is a robust measure that rank orders the data and takes the mean of the middle 60% of the data, reducing the potential effects of outliers. Two thresholds were acquired per electrode location for each masker condition, and a third was acquired if time allowed.

Contralateral masked thresholds—Masked thresholds were obtained by presenting a continuous masking pulse train in the right ear. The masker was initiated prior to the first probe and was presented continuously throughout the entire adaptive run. The location of the probe varied from adaptive run to adaptive run. The level of the probe was adjusted using the modified Bekesy protocol described above. All subjects were tested with both the *narrow* and *broad* masker conditions, and the masking condition was alternated from threshold

condition to threshold condition. Two thresholds were acquired per electrode location for each masker condition, and a third was acquired if time allowed.

4. Results

Robust statistical analyses were used to avoid the assumption of normality and minimize the effects of outliers (see also the supplemental digital content in Aronoff et al., 2016b). These included bootstrap analyses, which avoid assumptions of normality by using distributions based on the original data rather than an assumed normal distribution. These also included trimmed means, as described in the Methods section above.

The contralateral masking functions for each participant were obtained by subtracting the unmasked thresholds from the corresponding masked thresholds for both the broad and narrow contralateral masker in μA . The raw masked threshold differences are plotted on the contralateral masking functions shown on the upper half of Figure 3.

In order to assess the effect of broadening the current stimulation, the masking functions were normalized to the highest and lowest threshold for each masking condition for each subject. Normalization of the masking thresholds adjusts the masking functions to a common scale so that the broadness could be compared across maskers without a confound of any differences in the magnitude of masking. This was done as followed:

$$\text{Normalized threshold} = \frac{X - \text{Min}}{\text{Max} - \text{Min}}$$

where X refers to the amount of masking (in μA) at a particular electrode or virtual channel location for a given masker condition and Min and Max represents the minimum and maximum masked threshold difference, respectively, for that particular masker condition. As a result of this normalization, the normalized thresholds range from 0 to 1 for every subject. The normalized masking functions are shown on the bottom half of Figure 3.

The difference in broadness of the broad and narrow masking functions was evaluated using the normalized masking function. The effect of broadening the current shape of the masker was determined at probe locations that were one electrode apical and basal to the peak of the narrow masking function (Figure 4). The difference in thresholds for the broad and narrow normalized masking functions were analyzed using a percentile bootstrap pairwise comparison with 20% trimmed means, with familywise error controlled using Rom's method (Rom, 1990), resulting in an α of 0.025.

The results from this analysis revealed a significant difference between the broad and narrow contralateral masker ($p < 0.02$, Cohen's $d=0.8$) one electrode basal to the peak of masking, where the broader masker yielded larger normalized thresholds, indicating a broadening of the masking function. There was no significant difference for one electrode apical to the peak of masking ($p > .05$). One subject's data (I06) could not be analyzed for the basal comparison because the peak of the narrow masker masking function was at the very basal end of the array (electrode 16) resulting in an absent threshold one electrode basal to the peak for comparison of broadness to the broader masker. There was no systematic

relationship between the contralateral masker broadness and whether the subjects were simultaneously and sequentially bilaterally implanted, although this may simply reflect the small sample size (Figure 5).

To determine if the off-peak stimulation contributed to the magnitude of the peak of masking, the differences in peak magnitude of the broad and narrow raw masking functions were analyzed using a percentile bootstrap pairwise comparison with 20% trimmed means. The results indicated no significant difference in mean peak magnitudes of the masking function between the broad and narrow contralateral masker ($p=0.511$, $\alpha=0.05$) (Figure 6).

5. Discussion

The results indicated that the broader masker resulted in a broader masking function. This suggests that the contralateral masking function is not solely controlled by the peak of the masker. Instead, the results suggest that stimulation outside of the peak of the masker can influence the shape of the contralateral masking function. It is not clear from the current study whether stimulation locations more than one electrode (approximately 1 mm with the current population) from the center of the masker will also affect the masking functions. There was no significant difference in the magnitude of the peak of the raw masking functions between the two masker conditions. This suggests that the magnitude of the peak of the masking function predominantly reflects only the stimulation peak of the masking signal.

Contralateral masking without the MOC pathway

The contralateral masking functions acquired in this study add to a growing literature demonstrating contralateral masking in CI users (Aronoff et al., 2015; James et al., 2001; Lin et al., 2013; van Hoesel and Clark, 1997). Additionally, both the general shape and magnitude of the masking functions from this study resemble those found previously (e.g., Aronoff et al., 2015). Also consistent with previous literature (Aronoff et al., 2015; Lin et al., 2013), the masker did not affect thresholds for the entire array. Although there is evidence that the MOC efferent pathway drives the contralateral masking phenomenon in NH listeners, this study provides further evidence that contralateral masking can occur without the influence of the MOC pathway. However, as with previous studies on contralateral masking with CI users (Aronoff et al., 2015; James et al., 2001; Lin et al., 2013; van Hoesel and Clark, 1997), the current results were based on a relatively small sample size. Future studies with larger sample sizes are needed.

As seen previously (Aronoff et al., 2015), masked threshold were occasionally negative (i.e., audibility of the probe was improved in the presence of a contralateral masker). Although it is not possible to definitively determine the cause of this for each threshold, anecdotally subjects have noted that the contralateral masking tone can reduce their tinnitus, facilitating the detection of the tone.

Despite what appears to be different underlying mechanisms, there are some similarities between contralateral masking effects in NH and CI users. For example, in both populations, as the masker is shifted apically in one ear, the peak of the masking function also shifts

apically (Aronoff et al., 2015; Hughes, 1940; Ingham, 1957; Lin et al., 2013; Sherrick and Albernaz, 1961; Zwislocki, 1971). Similarly, for both NH and CI listeners, there is a systematic difference between the broadness of the contralateral and ipsilateral masking functions, with both groups exhibiting a sharper contralateral masking function compared to their ipsilateral masking functions (Aronoff et al., 2015; Mills et al., 1996). It is possible that these similarities reflect partially overlapping mechanisms.

The finding that the magnitude of the masking effect was not significantly different across the two masker conditions is not consistent with contralateral masking patterns in NH listeners. Snyder (1973) measured masked detection thresholds with different bandwidth maskers and found that the energy near the peak of the masker was the key determinant of the magnitude of masking. This study found that relocating energy from the peak of the masker to off-peak locations decreased the magnitude of the peak of contralateral masking. However, this is not consistent with data from otoacoustic emissions (OAE) studies, which indicate that a contralateral noise with a broader bandwidth is more effective in suppressing OAEs in the other ear when compared to a narrower band noise (Lisowska et al., 2002). It is not clear why contralateral masking and OAE data appear to disagree for NH listeners, especially given that they are both believed to rely on the effects of the MOC pathway (Guinan, 2006).

Implications for using current shaping techniques with bilateral CI users

The results from this study have implications for how current shaping techniques will affect bilateral CI users. The results suggest that the relative broadness of stimulation is maintained when signals from the two ears interact. This is important because the broad nature of monopolar stimulation may decrease the detrimental effects of stimulating mismatched locations in the two cochleae (Goupell et al., 2013). When signals from the two ears are not delivered to matched locations (i.e., there is an interaural mismatch), interaural time difference (ITD) sensitivity, interaural level difference (ILD) sensitivity, and the ability to fuse sounds from the two ears into a single percept can be detrimentally affected (Aronoff et al., 2015b; Goupell et al., 2013; Kan et al., 2013; Long et al., 2003; Poon et al., 2009). For CI users, such interaural mismatches are common (Aronoff et al., 2016a; Kan et al., 2013; Long et al., 2003; Poon et al., 2009). With broad stimulation, even if the center of stimulation is mismatched across ears, the edges of the broad stimulation may still activate matched locations. Given the implication of this study that the current shape of the electrode stimulation is, to some extent, maintained across the two ears along the central auditory system, techniques that narrow the current shape, such as tripolar stimulation (Bierer and Faulkner, 2010; Landsberger and Srinivasan, 2009; Srinivasan et al., 2013; Srinivasan et al., 2010) may increase CI users' sensitivity to interaural mismatches. However, studies directly comparing sensitivity to interaural mismatches with different current shaping techniques are needed.

The findings from this study also have implications for bilateral processing strategies. For instance, interleaving interaurally matched electrode stimulation is a strategy that tries to minimize within ear channel interaction by splitting signals from neighboring frequency regions to opposite ears (Aronoff et al., 2016b), effectively increasing the distance between

stimulation sites within each ear. The current results suggest that such strategies, when combined with current focusing techniques, would receive additional reduction in across-ear channel interaction in addition to a reduction in within-ear channel interaction.

Additionally, the results suggest that focusing techniques, e.g. tripolar or partial tripolar stimulation, may potentially improve spectral resolution across ear as well as within ear as a result of reduced channel interaction, providing benefits to binaural abilities that rely on spectral resolution.

There are also implications for CI processing strategies that mimic the effects of the MOC pathway (Lopez-Poveda et al., 2016). These strategies utilize both processors in bilateral CI users in an attempt to recreate the dynamic basilar membrane compression, which is dependent on the MOC reflex in normal hearers. This is achieved through a dynamic back-end compression stage, rather than the standard fixed logarithmic compression function used in standard CI sound processing strategies. The occurrence of contralateral masking in this and other studies (Aronoff et al., 2015; Lin et al., 2013; van Hoesel and Clark, 1997) suggest that some of the contralateral effects attributed to the MOC pathway are still occurring for CI users. This raises the possibilities that MOC-emulating processing strategies may duplicate some of the effects already occurring for these patients, resulting in overcompensation for the effects of the contralateral signal.

6. Conclusions

This study found that a broader masker resulted in a broader contralateral masking function. This suggests that stimulation outside of the peak of the masker impacts the contralateral masking function for bilateral CI users.

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List of abbreviations

CI	cochlear implant
ILD	interaural level difference
ITD	interaural time difference
MOC	medial olivocochlear
NH	normal hearing
OAE	otoacoustic emission
OHC	outer hair cell
SNHL	sensorineural hearing loss

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Highlights

- A broader masker results in broader contralateral masking functions for cochlear implant subjects
- A broader masker does not significantly affect the magnitude of contralateral masking for this population
- Stimulation shapes are relatively maintained within central auditory system

Figure 1.
Schematic representation of the narrow masker (left) and broad masker (right) with electrode numbers (color version online).

Figure 2.
Raw unmasked contralateral thresholds for each participant (color version online).

Figure 3.

(Upper half) Raw contralateral masking thresholds differences for both masking conditions with peak threshold differences in μA labeled for each bilateral CI participant at varying probe electrode locations. Dashed grey line refers to a threshold difference of 0 μA . (Bottom half) Normalized masking functions for each subject at varying probe electrode locations (color version online).

Figure 4.

Normalized contralateral masking functions for both broad and narrow maskers, centered at the peak threshold location, pooled across subjects. Bolded lines represents the trimmed mean threshold across subjects and shaded region pertains to the winsorized standard error for each corresponding masker. $\pm(\#)$ electrodes refers to the number of electrodes away from the peak (for example +1 electrode is one electrode basal and -1 electrode is one electrode apical from the peak location) (color version online).

Figure 5.

Trimmed mean differences of the normalized thresholds at plus and minus one electrode away from the peak masking location for each bilateral subject, color coded based on whether simultaneously or sequentially implanted (color version online).

Figure 6.

Trimmed mean of raw peak difference (broader masker threshold minus narrow masker threshold) in μA for each bilateral subject, color coded based on whether simultaneously or sequentially implanted (color version online).

Table 1

Subject details provided. Under the Gender column, M indicates male and F indicates female. L indicates the left ear and R indicates the right ear throughout the table. SNHL indicates sensorineural hearing loss

Subject ID	Gender	Age (years)	Age at onset of hearing loss (in years)	Etiology	Duration of processors activated (in years)
I05	M	58	5	Unknown	L & R:13
I06	F	58	38–39	Genetic SNHL	L:2; R:4
I07	M	55	30	Familial	L & R: 2
I10	F	50	29	Sudden (autoimmune)	L:2; R:3
I11	M	68	L: 9–10; R: 57	Unknown	L:3; R:11
I14	M	55	in 20s	R:progressive; L:sudden	L:3; R:4