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Perceptually aligning apical frequency regions leads to more binaural fusion of speech in a cochlear implant simulation

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Abstract

For bilateral cochlear implant users, the left and right arrays are typically not physically aligned, resulting in a degradation of binaural fusion, which can be detrimental to binaural abilities. Perceptually aligning the two arrays can be accomplished by disabling electrodes in one ear that do not have a perceptually corresponding electrode in the other side. However, disabling electrodes at the edges of the array will cause compression of the input frequency range into a smaller cochlear extent, which may result in reduced spectral resolution. An alternative approach to overcome this mismatch would be to only align one edge of the array. By aligning either only the apical or basal end of the arrays, fewer electrodes would be disabled, potentially causing less reduction in spectral resolution. The goal of this study was to determine the relative effect of aligning either the basal or apical end of the electrode with regards to binaural fusion. A vocoder was used to simulate cochlear implant listening conditions in normal hearing listeners. Speech signals were vocoded such that the two ears were either predominantly aligned at only the basal or apical end of the simulated arrays. The experiment was then repeated with a spectrally inverted vocoder to determine whether the detrimental effects on fusion were related to the spectral-temporal characteristics of the stimuli or the location in the cochlea where the misalignment occurred. In Experiment 1, aligning the basal portion of the simulated arrays led to significantly less binaural fusion than aligning the apical portions of the simulated array. However, when the input was spectrally inverted, aligning the apical portion of the simulated array led to significantly less binaural fusion than aligning the basal portions of the simulated arrays. These results suggest that, for speech, with its predominantly low frequency spectral-temporal modulations, it is more important to perceptually align the apical portion of the array to better preserve binaural fusion. By partially aligning these arrays, cochlear implant users could potentially increase their ability to fuse speech sounds presented to the two ears while maximizing spectral resolution.

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Keywords

Binaural hearing; cochlear implants; binaural fusion

1. Introduction

Bilateral cochlear implant users often do not perceive the same pitch in both ears when stimulating electrodes that receive the same frequency allocation for the left and right electrode arrays. These mismatches may result from differences in insertion depth and cell survival along the cochlea (Aschendorff et al., 2005; Fayad et al., 1991; Marsh et al., 1993; Reiss et al., 2011; Svirsky et al., 2015).

Complete perceptual alignment of the two electrode arrays is ideal, however it is often impossible due to factors such as electrode array insertion depth differences. Electrode numbers, reflecting the distance of an electrode from the basal or apical end of the array, do not predict the cochlear location of a given electrode (Landsberger et al., 2015) or which electrodes in the left and right ear are best to pair together (Hu et al., 2015; Long et al., 2003; Poon et al., 2009). However, clinical fittings remain dependent on electrode numbers to assign frequency allocations in both ears. Although the detrimental effects of mismatch may be partly mediated by adaptation (Reiss et al., 2008; Reiss et al., 2011; Reiss et al., 2015), CI users may not be able to fully compensate for the physically mismatched arrays, particularly if the mismatch is large enough (Guerit et al., 2014; Reiss et al., 2011).

This can pose a problem in regards to fusion (Aronoff et al., 2015; Goupell et al., 2013; Kan et al., 2013). As mismatch increases, fusion decreases. This can also have detrimental effects on the utilization of interaural time differences (ITDs) and interaural level differences (ILDs; Francart et al., 2007; Long et al., 2003; Poon et al., 2009). As the magnitude of the mismatch between ears increases, sensitivity to ITD's and ILD's decreases, which can reduce the ability to localize and lateralize sounds appropriately (Francart et al., 2007; Long et al., 2003; Poon et al., 2009). One option to address this mismatch is to use a subset of each array, using only those electrodes that can be aligned across ears and disabling the electrodes at the ends of the arrays that do not perceptually align to any stimulation locations on the other array (see Figure 1). However, doing so may shorten the usable portions of each array. Shortening the usable portions of the array results in the input frequency range being compressed into a smaller cochlear region (i.e., spectral compression), which could have detrimental effects on tasks such as listening to speech in noisy environments. A second option would be to match up only either the apical or basal ends of the array while leaving the other end mismatched (see Figure 1). This option would use a larger extent of the electrode array, resulting in less spectral compression. By minimizing spectral compression and maximizing the useable portion of the electrode array between the two ears, this approach could be the optimal compromise between leaving the arrays perceptually mismatched and perceptually aligning the two arrays by dramatically spectrally compressing the signal. However, it is unclear whether it would be more beneficial to align the apical or basal end of the array with this approach.

The goal of this study was to determine whether aligning the apical or basal portions of the array would better preserve binaural fusion of speech stimuli. To test this, binaural fusion was measured in normal hearing subjects using vocoded stimuli where either the apical or basal edges of the simulated arrays were perceptually aligned.

2. Experiment 1

2.1 Methods

2.1.1 Participants—Nine listeners, 6 female and 3 male, ages ranging from 21 to 23 were tested. Subjects' pure-tone thresholds were 25 dB HL from 0.25 to 8 kHz. Thresholds did not differ by more than 15 dB between the left and right ear.

2.1.2 Stimuli—The stimuli for the experiment were based on those used in Aronoff et al. (2015) and consisted of the words *yam* and *pad*, prerecorded by a male speaker. The stimuli were vocoded by first, high-pass filtering at 1200 Hz with a 6 dB per octave roll-off to add pre-emphasis. Then eight bandpass filters were used for each ear to simulate an eight-channel cochlear implant with an analysis filter frequency range between 200 Hz and 7 kHz implemented using a 4th order Butterworth filter with forward filtering. These filters were designed to sample frequency ranges that were equally spaced along the cochlea based on the equation by Greenwood (1990). The envelope of each band was extracted by half-wave rectification followed by low pass filtering at 160 Hz using a 4th order Butterworth filter. These parameters were chosen because they are similar to what are typically found in cochlear implants (e.g., Zeng, 2004). The envelopes for each channel were then convolved with narrowband noise. Finally, all channels were summed for each ear.

Perceptual mismatches were created by spectrally compressing the signal for only the right ear, with an average spectral compression of 0.2, 0.7, 1.3, and 1.8 mm across the entire array based on the equation by Greenwood (1990). For the left ear, the carrier filters were the same as the analysis filters and covered a cochlear extent of 19.2 mm. Although the analysis filters were unchanged for the right ear, the spectral compression was implemented by having the carrier filters for that ear cover a smaller extent of the cochlea, ranging from 15.5 to 18.8 mm, resulting in an average spectral compression of 1.8 to 0.2 mm. Spectrally compressing apically maintained the same uppermost center frequency in the left and right carrier filters, while compressing basally maintained the same lowermost center frequency in the left and right carrier filters (see Figure 2 and 3, left panel and Table 1).

2.1.3 Equipment—The stimuli were presented using an Edirol UA-25 external soundcard and delivered over Sennheiser HDA 200 headphones in a double-walled sound attenuating booth. The left and right headphones were separately calibrated with the SoundCheck 12.0 software using an artificial ear, microphone, and preamplifier (Brüel and Kjær type 4153, 4192, and 2669, respectively).

2.1.4 Procedures—The subjects were seated in front of a monitor with mouse accessibility within a double-walled sound attenuating booth. The stimuli were presented at 65 dB (A). Participants were presented with the following question on the monitor: "Do you hear the same sound at both ears or a different sound at each ear." A two alternative forced

choice task was presented to participants to choose between whether the sounds were the “same” or “different.” The task was repeated 30 times for both apical and basal compression locations with compression magnitudes of 0.2, 0.7, 1.3, and 1.8mm. The sequence of trials was initiated once the participant entered in a response. Trials were grouped into blocks with stimuli from all conditions pseudorandomly combined within each block, and testing typically took less than 2 hours.

3. Results

Robust statistical techniques were adopted to minimize the potential effects of outliers and non-normality (see the appendix in the supplemental digital content in Aronoff et al., 2016). 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, which are a cross between means and medians.

A two way repeated measures ANOVA (Location $\times$ Magnitude) using 20% trimmed means was conducted. There was a main effect of Location ($p < 0.001$), a main effect of Magnitude ($p < 0.0001$), and a significant interaction ($p < 0.01$). To investigate the interaction, the difference in the amount of fusion with apical versus basal compression was compared for the 0.2, 0.7, 1.3, and 1.8 mm conditions using percentile bootstrap pairwise comparisons with 20% trimmed means with alpha adjusted using Rom’s method (Rom, 1990) to correct for family wise error. There was a significant difference between the effects of apical and basal compression for the 1.3 and 1.8 mm conditions, but not for the 0.7 and 0.2 mm conditions, with poorer fusion with an apical mismatch (see Table 2 for details and Figure 4, left panel).

4. Discussion

The results for Experiment 1 revealed that, for large mismatches, mismatches in the apical portions of the simulated electrode arrays were significantly more detrimental for binaural fusion than mismatches in the basal portions of the simulated arrays. This difference between the effects of apical and basal alignment could be due to either the spectral-temporal characteristics of the stimuli or the location in the cochlea that received the signal. Speech has predominantly low frequency spectral-temporal modulations, thus, creating a mismatch in a low frequency region may distort a crucial cue used to fuse the ears together. However, the difference between the effects of apical and basal alignment could reflect different specializations for different regions of the cochlea, and it may be that the binaural auditory system relies on the apical portions of the cochlea for binaural fusion. If the differences in binaural fusion ability are dependent on cochlear location, binaural fusion should be affected by which cochlear region contains the mismatched portion of the signal regardless of the spectral content of the stimulus. In contrast, if fusion is more dependent on spectral-temporal characteristics of the stimuli, binaural fusion should be best when the spectral temporal modulations in the signal are delivered to a region with minimal mismatch. To distinguish these possibilities, the study was repeated using a spectrally inverted vocoder.

5. Experiment 2

Experiment 2 replicated the same test measures and protocol as Experiment 1, with the exception of using a spectrally inverted vocoder, described below.

5.1 Methods

5.1.1 Participants—Eight listeners, all female, ages ranging from 20 to 24 were tested. Subjects had pure-tone thresholds 25 dB HL from 0.25 to 8kHz. Thresholds did not differ by more than 15 dB between the left and right ear. None of the participants from Experiment 1 participated in this experiment.

5.1.2 Stimuli—Stimuli for Experiment 2 were similar to those from Experiment 1, except that the signal was spectrally inverted by the vocoders. This was done by convolving the envelopes from the high frequency analysis filters with low frequency carriers and the envelopes from the low frequency analysis filters with high frequency carriers (See Figures 2 and 3, right panel; Table 3). As with Experiment 1, only the right ear was spectrally compressed. In this experiment, low frequency information that would normally be sent to the apex was sent to the base and high frequency information that would normally be sent to the base was sent to the apex.

5.1.3 Procedures—The same procedures were used as in Experiment 1. There were 30 trials per condition. Trials were grouped into blocks, and testing typically took less than 2 hours.

6. Results

A two way repeated measures ANOVA (Location $\times$ Magnitude) using 20% trimmed means was conducted. There was a main effect of location ($p < 0.01$), a main effect of magnitude ($p < 0.001$), and a significant interaction ($p < 0.0001$). To investigate the interaction, the difference in the amount of fusion with apical versus basal compression was compared for the 0.2, 0.7, 1.3, and 1.8 mm conditions using percentile bootstrap pairwise comparisons with 20% trimmed mean and alpha adjusted using Rom's correction (Rom, 1990) to correct for familywise error. There was a significant difference between the effects of apical and basal compression for the 1.3 and 1.8 mm conditions, but not for the 0.7 and 0.2 mm conditions, with poorer fusion with a basal mismatch (for details see Table 4; Figure 4, right panel).

7. Discussion

The results for Experiment 2 revealed that, for large mismatches, mismatches in the basal portions of the simulated electrode arrays were significantly more detrimental for binaural fusion than mismatches in the apical portions of the simulated arrays. These results are the reverse of those found in Experiment 1. The implications of this reversal in results will be discussed below in the General Discussion section.

8. General Discussion

The results for Experiment 1 revealed that, for large mismatches, aligning the apical portions of the electrode arrays was significantly better for binaural fusion than aligning the basal portions of the arrays. The results from Experiment 2 revealed that basal alignment was better for fusion than apical alignment when the stimuli were spectrally inverted. In the case of Experiment 2, low frequency weighted speech information, which would have typically been presented to the apical region of the cochlea, was delivered to the basal regions of the cochlea. More fusion in both experiments was observed when the spectral temporal modulations in the signal were delivered to an area with minimal mismatch, which suggests that the preservation of the spectral temporal characteristics of the stimuli contribute to the extent of binaural fusion more so than the place of stimulation along the cochlea.

8.1 The effects of mismatches

In the current study, as the magnitude of mismatch increased, a decrease in fusion occurred. Previous studies have shown a similar pattern between magnitude of mismatch and fusion for both vocoder and CI studies (Aronoff et al., 2015; Goupell et al., 2013; Kan et al., 2013). However a place mismatch between electrode arrays has been found to affect more than just the ability to fuse sounds. ITD and ILD sensitivity have also been shown to reduce as mismatches increase and as a result reduces the ability to localize and lateralize sounds using spatial cues (Francart et al., 2007; Goupell et al., 2013; Kan et al., 2013; Long et al., 2003; Poon et al., 2009).

8.2 Differences between CI simulations and CI users

Both vocoder and CI studies have revealed comparable patterns of results regarding the effects of mismatches on binaural abilities, suggesting that vocoder simulations are able to emulate CI mismatches and their debilitating effects (Goupell et al., 2013; Kan et al., 2013; Laneau et al., 2006; Long et al., 2003; Poon et al., 2009). Although there is a general similarity between results with vocoder and CI studies, there are limitations in extrapolating from CI simulations to CI users. A primary limitation is that the magnitude of the effect of misalignments between the ears is likely to be reduced for CI users. One factor that can reduce the impact of misalignments for CI users is adaptation. Over time, cochlear implant recipients may learn to partially adapt to these misalignments (Reiss et al., 2011; Vermeire et al., 2015). Even though this adaptation may not be sufficient to completely overcome the detrimental effects of misalignments (e.g., Reiss et al., 2011), partial adaptation can result in greater preservation of fusion.

A second factor is the broad spread of activation that occurs with electrical stimulation that was not simulated in the current vocoder. Increased spread of activation will mean that, for moderate misalignments, overlapping neural populations in the two ears are still stimulated, preserving fusion (Goupell et al., 2013). Consistent with this notion, Reiss et al. (2014) showed that CI users will binaurally fuse pitches over a much larger range of mismatch compared to normal hearers. Thus, the magnitude of the effect of apical or basal compression is likely to be different for CI users, but the general trend is likely to be the same, but further studies are needed with CI users.

9. Conclusion

The results from the current study suggest that, when necessary, choosing to align the apical portion of the arrays rather than the basal portion will yield better fusion for speech. Aligning just one end of the array increases the useable portion of the electrode array compared to aligning both regions, potentially leading to better speech understanding in noisy environments.

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List of Abbreviations

ITD	Interaural time difference
ILD	Interaural level difference
ANOVA	Analysis of variance
mm	millimeters

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- The benefits of aligning different ends of a simulated array were investigated.
- Aligning the apical end of the array led to better binaural fusion of speech.
- Aligning the basal end led to better binaural fusion of spectrally inverted speech.
- Results suggest in everyday use it is more important to align the apical end.

Figure 1.

Two possible approaches to handling mismatches across bilateral arrays. The grey portions are the regions of each array that do not perceptually match anything on the other ear, while the yellow sections are the matched portions of the arrays. The dashed squares indicate the part of the array that could be removed to align the arrays either apically or basally. Either disabling the electrodes at the apical end that cannot be perceptually aligned while leaving the basal electrodes mismatched (**left**), or disabling the electrodes at the basal end that cannot be perceptually aligned while leaving the apical electrodes mismatched (**right**).

Figure 2.

A schematic of the vocoder simulating basally aligned arrays used in Experiment 1 (**Left panel**). A schematic of the spectrally inverted vocoder simulating basal alignment used in Experiment 2, which convolved the envelopes from the high frequency analysis filters with low frequency carriers and the envelopes from the low frequency analysis filters with high frequency carriers (**Right panel**).

Figure 3. Example spectrograms of the word “yam” vocoded with no compression, basal compression, and apical compression as in Experiment 1 (**Left Panel**) and with the spectrally inverted vocoder as in Experiment 2 (**Right Panel**).

Figure 4.

20% trimmed means for each condition. Mismatches in the apical end were significantly more detrimental than mismatches in the basal end for large mismatches in Experiment 1.

(Left panel) Mismatches in the basal end were significantly more detrimental than mismatches in the apical end for large mismatches in Experiment 2. **(Right panel)**

Figure 1.

Basal Compression										Apical Compression			
0.2 mm				0.7 mm				1.3 mm		1.8 mm		Lower Bounds	Upper Bounds
Lower Bounds	Upper Bounds	Lower Bounds	Upper Bounds	Lower Bounds	Upper Bounds	Lower Bounds	Upper Bounds	Lower Bounds	Upper Bounds	Lower Bounds	Upper Bounds		
466	558	361	663	201	357	205	352	209	346	213	341	466	558
721	830	558	953	357	583	352	559	346	537	341	515	721	830
1083	1208	830	1346	583	909	559	854	537	802	515	752	1083	1208
1597	1733	1208	1880	909	1382	854	1271	802	1169	752	1073	1597	1733
2325	2462	1733	2606	1382	2068	1271	1863	1169	1678	1073	1510	2325	2462
3357	3472	2462	3591	2068	3061	1863	2703	1678	2385	1510	2102	3357	3472
4820	4874	3472	4929	3061	4499	2703	3893	2385	3366	2102	2907	4820	4874
6895	6820	4874	6745	4499	6583	3893	5580	3366	4726	2907	4000	6895	6820

Table 2

The 95% confidence intervals and 20% trimmed mean scores for apical and basal compression comparisons for varying magnitudes of mismatch in Experiment 1.

Conditions being compared	95% confidence interval	20% trimmed mean
1.8mm apical minus 1.8mm basal compression	−44.01 to −3.83	26.7
1.3mm apical minus 1.3mm basal compression	−54.99 to −11.17	32.4
0.7mm apical minus 0.7mm basal compression	−20.49 to 10.73	5.2
0.2mm apical minus 0.2mm basal compression	−6.19 to 5.7	0.9

Figure 2.

Basal Compression										Apical Compression			
0.2 mm				0.7 mm				1.3 mm		1.8 mm		1.3 mm	
Lower Bounds	Upper Bounds	Lower Bounds	Upper Bounds	Lower Bounds	Upper Bounds	Lower Bounds	Upper Bounds	Lower Bounds	Upper Bounds	Lower Bounds	Upper Bounds	Lower Bounds	Upper Bounds
6895	6820	4929	6745	4499	6583	3893	5580	3366	4726	2907	4000	2907	4000
4820	4874	3591	4929	3061	4499	2703	3893	2385	3366	2102	2907	2102	2907
3357	3472	2606	3591	2068	3061	1863	2703	1678	2385	1510	2102	1510	2102
2325	2462	1880	2606	1382	2068	1271	1863	1169	1678	1073	1510	1073	1510
1597	1733	1346	1880	909	1382	854	1271	802	1169	752	1073	752	1073
1083	1208	953	1346	583	909	559	854	537	802	515	752	515	752
721	830	663	953	357	583	352	559	346	537	341	515	341	515
466	558	450	663	201	357	205	352	209	346	213	341	213	341

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Table 4

The 95% confidence intervals and 20% trimmed mean scores for apical and basal compression comparisons for varying magnitudes of mismatch in Experiment 2.

Conditions being compared	95% confidence interval	20% trimmed mean
1.8mm apical minus 1.8 basal compression	11.65 to 47.27	25.6
1.3mm apical minus 1.3 basal compression	6.23 to 59.42	30.1
0.7mm apical minus 0.7 basal compression	-3.41 to 19.93	2.3
0.2mm apical minus 0.2 basal compression	-3.07 to 9.58	2.3