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Unilateral spectral and temporal compression reduces binaural fusion for normal hearing listeners with cochlear implant simulations

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Abstract

Patients with single sided deafness have recently begun receiving cochlear implants in their deaf ear. These patients gain a significant benefit from having a cochlear implant. However, despite this benefit, they are considerably slower to develop binaural abilities such as summation compared to bilateral cochlear implant patients. This suggests that these patients have difficulty fusing electric and acoustic signals. Although this may reflect inherent differences between electric and acoustic stimulation, it may also reflect properties of the processor and fitting system, which result in spectral and temporal compression. To examine the possibility that unilateral spectral and temporal compression can adversely affect binaural fusion, this study tested normal hearing listeners' binaural fusion through the use of vocoded speech with unilateral spectral and temporal compression. The results indicate that unilateral spectral and temporal compression can hinder binaural fusion and thus may adversely affect binaural abilities in patients with single sided deafness who use a cochlear implant in their deaf ear.

Keywords

Binaural fusion; single sided deafness; binaural hearing; vocoder

2. Introduction

Cochlear implants provide considerable benefits for patients with bilateral deafness, often yielding dramatic improvements in localization, as well as better speech understanding in

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noise (Dunn et al. 2010; Dunn et al. 2008; van Hoesel 2004). Patients with single sided deafness (SSD) have recently begun receiving cochlear implants in their deaf ear (Arndt et al. 2010; Punte et al. 2011; Vermeire et al. 2009). These patients gain a significant benefit from having a cochlear implant. However, despite this benefit, they are considerably slower to develop binaural skills compared to bilateral cochlear implant patients. For example, summation (i.e., the added benefit of having a second ear when the speech and noise are co-located) occurs nearly instantaneously post implantation for patients receiving bilateral cochlear implants (Dunn et al. 2012; Eapen et al. 2009). In contrast, for SSD patients, summation often does not occur or can take at least a year to develop (Arndt et al. 2010; Punte et al. 2011; Vermeire and Van de Heyning 2009).

The relatively slow development of binaural abilities such as summation suggests that SSD patients may have difficulty fusing an electric and acoustic signal. Although this may reflect differences between the nature of electrical and acoustical stimulation, it may also reflect differences that are not inherent properties of the stimulation method. In the electric ear, the acoustic range is typically spectrally compressed (or sometimes stretched), resulting in unilateral spectral compression. For example, although the electrodes on cochlear implant arrays typically span from approximately 17 to 26mm, the input filters have default center frequencies that cover approximately 19mm to 23mm of the cochlea. With an acoustic and an electric ear, this will result in a spectral mismatch between ears that varies along the array. Spectral mismatches resulting from spectral shifts, which could be caused by such factors as insertion depth differences, can be detrimental for binaural abilities (Goupell et al. 2013; Kan et al. 2013; Yoon et al. 2013), and spectral compression that varies along the cochlea may be even more detrimental.

In addition to spectral compression, cochlear implant stimulation also typically results in temporal compression. In an acoustically hearing ear there is a frequency-dependent traveling wave delay that can be larger than 5 ms at low frequencies (Neely et al. 1988). This means that, for the acoustically hearing ear, a low frequency stimulus will activate the cochlea milliseconds after a simultaneously played high frequency stimulus, while for the electric ear, the same high and low frequency stimuli will stimulate the cochlea at virtually the same time. This will result in the stimulation of the electric ear being temporally compressed relative to the stimulation of the acoustic ear. Because common onset can be an important cue for grouping sounds (Bregman 1990), frequency-dependent timing differences between the electric and acoustic ear may reduce binaural fusion.

Experiment 1

The goal of Experiment 1 was to investigate whether unilateral spectral and temporal compression, as would occur for patients with an electric and acoustic ear, reduces binaural fusion.

3. Methods

3.1 Participants

Twelve normal hearing listeners participated in this experiment. All participants had pure tone thresholds ≤ 25 dB HL from .25 to 8 kHz. Thresholds did not differ by more than 15 dB between the left and right ear.

3.2 Stimuli

The stimuli for the experiment consisted of the words *yam* and *pad*, spoken by a male speaker. The stimuli for both the left and right ear were vocoded. This allowed the investigation of the effects of unilateral spectral and temporal mismatches without the confound of the effect of combining a vocoded signal in one ear and an unprocessed signal in the other.

3.3 Vocoding

The stimuli were first high-pass filtered at 1200 Hz with a 6 dB per octave roll-off to add pre-emphasis. Next, eight bandpass filters were used for each ear to simulate an eight-channel cochlear implant, with a frequency range between 200 Hz and 7 kHz 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. The envelopes for each channel were then convolved with narrowband noise. Finally, all channels were summed for each ear and the waveforms were combined to create a single two-channel audio signal.

3.4 Spectral and Temporal Manipulations

Three conditions were tested (see Figure 1). As a baseline, participants were tested with the same signal sent to both ears (**Identical condition**). For the **Spectral Compression condition**, the filters for the narrowband carrier in one ear were equally spaced along the cochlea covering 1 to 7 kHz based on the equation by Greenwood (1990). As in all conditions, the analysis filters for both ears were equally spaced along the cochlea covering 200 to 7 kHz. For the **Temporal Compression condition**, the signal for each filter band in one ear was delayed by subtracting the traveling wave delay that would occur at the center of that filter band (Greenberg et al. 1998), countering the naturally occurring traveling wave delay. When the inverse delay that was applied to the signal combines with the naturally occurring traveling wave delay in the listeners' ear, the resulting activation throughout the cochlea will occur nearly simultaneously, effectively temporally compressing the signal relative to the opposite ear. All stimuli were bandpass filtered from 500 Hz to 4000 Hz with 8th order Butterworth filters. This minimized the ability of participants to listen to frequency regions dominated by one ear in the spectral compression condition. Additionally, pilot data suggested that this filtering reduced floor and ceiling effects, increasing the ability to see differences between conditions.

3.5 Procedures

The stimuli were presented using an Edirol UA-25 external soundcard and delivered over Sennheiser HDA 200 headphones. The left and right headphone were separately calibrated. The stimuli were presented at 65 dB(A). Participants were presented with a screen with the following question: “Do you hear the same sound at both ears or a different sound at each ear.” Participants had two buttons to select from, one labeled “same” and one labeled “different.” The next trial was initiated once the participant entered in a response. There were 60 trials per condition. Trials were grouped into blocks, and testing typically took less than an hour. For the Spectral and Temporal Compression conditions, the ear containing the spectral or temporal compression was counterbalanced across trials.

4. Results

Robust statistical techniques were adopted to minimize the potential effects of outliers and non-normality (see the Appendix in Aronoff et al. 2011). 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 include trimmed means, a cross between means and medians.

A percentile-*t* bootstrap repeated measures analysis of variance (ANOVA) with 20 % trimmed means indicated that the probability of fusing the sound from the left and right ear (i.e., responding “same”) was significantly affected by condition ($F_{crit} = 6.5$, $F_t = 43.1$, where $F_t > F_{crit}$ indicates significant results for $\alpha = 0.05$). Post-hoc analyses were conducted using percentile bootstrap pairwise comparisons with 20% trimmed means and familywise error controlled using Rom’s correction (Rom, 1990) to determine if fusion was significantly decreased with both unilateral spectral and temporal compression. The results indicated that spectral and temporal compression significantly decreased the amount of fusion compared to the Identical condition ($p < .0001$). Additionally, there was significantly less fusion with the Spectral Compression condition than with the Temporal Compression condition ($p < .0001$; see Figure 2).

5. Discussion

In this experiment, both unilateral spectral and temporal compression were found to reduce binaural fusion for normal hearing listeners. There was considerable variability for the temporal compression condition. This may suggest that the importance of temporal similarity between ears varies across individuals. Alternatively, this may reflect reduced variability in the Identical and Spectrally compressed conditions because of floor and ceiling effects. Although both spectral and temporal compression result from the fitting and processing algorithms in cochlear implants, for bilateral cochlear implant patients this would generally result in bilaterally matched spectral and temporal compression. In contrast, for SSD patients with a cochlear implant in one ear, this can result in unilateral spectral and temporal compression. The results suggest that spectral and temporal compression may be two factors slowing the development of binaural abilities in SSD patients who receive a cochlear implant in their deaf ear.

The results indicated that spectral compression was significantly more detrimental to binaural fusion than temporal compression, but those results should be interpreted with caution. First, in bandpass filtering the stimuli, the low frequency region of the signal was removed, which is where the largest traveling wave delay normally occurs. Thus, the reduced effect of temporal compression may reflect the bandpass filtering rather than indicating that the impact of temporal compression is particularly weak. Second, with smaller amounts of spectral compression, the effect of spectral compression may be reduced. Experiment 2 investigated that possibility.

Experiment 2

Experiment 1 demonstrated that unilateral spectral compression can negatively affect binaural fusion. However, the amount of spectral compression was an extreme case, compressing the equivalent of a frequency region that would span 19.2mm of the cochlea into a space of 11.6mm array. Although it is possible to have active electrodes that only span 11.6mm, particularly with a partial insertion, such a short array and such a large mismatch across ears is unlikely. The goal of this experiment was to determine whether unilateral spectral compression was still detrimental when simulating more typical array lengths.

6. Methods

6.1 Participants

Eight normal hearing listeners participated in this experiment. All participants had pure tone thresholds ≤ 25 dB HL from .25 to 8 kHz. Thresholds did not differ by more than 15 dB between the left and right ear.

6.2 Stimuli

Vocoding followed the same procedure as described in section 3.3. For all vocoded conditions, the analysis filters encompassed 0.2–9kHz, this corresponded to center frequencies that covered an approximately 21mm extent along the cochlea. Although this is a larger frequency range than is typical used for patients, this was done so that the center frequency for the carrier filter for the most basal channel was the same for all vocoded conditions to minimize conflating spectral compression and spectral shift. Varying amounts of spectral compression were simulated by shifting the carrier filters for the apical end to cover an approximately 17mm, 20mm, or 23mm extent of the cochlea, consistent with typical electrode array lengths in commercial devices. The simulated arrays are shown in Figure 3. Note that for the 23mm simulated array, the ear with the matching analysis and carrier filters is the spectrally compressed ear relative to the other side (i.e., the 23mm simulated array resulted in spectral expansion).

For all conditions, the **left** ear was either presented with the original unprocessed sound (**Unprocessed**) or with the 21mm vocoded stimulus where the analysis and carrier filters were the same (**Tonotopically matched**). The left ear stimulus was paired with a right ear that was either unprocessed, contained the 21mm tonotopically matched vocoded stimulus, or the vocoded stimuli simulating a **20mm**, **23mm** or **17mm** array.

6.5 Procedures

The procedures were identical to those described in Experiment 1, except there were 100 trials per condition and the left ear was always presented with either the Unprocessed or Tonotopically Matched stimuli.

7. Results

Vocoded stimuli

A percentile-*t* bootstrap repeated measures ANOVA with 20 % trimmed means indicated that the probability of fusing the sound from the left and right ear (i.e., responding “same”) was significantly affected by condition ($F_{crit} = 4.6$, $F_t = 22.0$, where $F_t > F_{crit}$ indicates significant results for $\alpha = 0.05$). Post-hoc analyses were conducted using percentile bootstrap pairwise comparisons with 20% trimmed means and familywise error controlled using Rom’s correction (Rom, 1990) to determine if fusion was significantly decreased with varying amounts of unilateral spectral compression. The results indicated that unilateral spectral compression was significantly detrimental to fusion ($p < .05$ for all comparisons). Additionally, changing the amount of spectral compression significantly changed the probability of binaural fusion ($p < .05$ for all comparisons; see Figure 4). A bootstrap mixed effect regression was used to determine the relationship between the probability of binaural fusion and the average difference in mm between the center frequencies for the two ears. The results indicated that there was a significant relationship between the two, with each mm of average mismatch yielding a median 25.7 percent decrease in the probability of fusing the two sounds (95% confidence interval: 0.1 to 31.4 percent; see Figure 5).

Unprocessed stimuli

A percentile-*t* bootstrap repeated measures ANOVA with 20 % trimmed means indicated that the probability of fusing the sound from the left and right ear (i.e., responding “same”) was significantly affected by condition ($F_{crit} = 3.5$, $F_t = 29.245$, where $F_t > F_{crit}$ indicates significant results for $\alpha = 0.05$). Post-hoc analyses were conducted using percentile bootstrap pairwise comparisons with 20% trimmed means and familywise error controlled using Rom’s correction. These indicated that combining a vocoded ear with an ear receiving an unprocessed stimulus significantly reduced binaural fusion compared to when both ears received unprocessed stimuli ($p < .05$ for all comparisons). However, the degree of spectral compression had no significant effect ($p > .05$ for all comparisons), possibly because combining an unprocessed ear and a vocoded ear yielded floor effects (see Figure 6).

5. Discussion

In this experiment, unilateral spectral compression was found to occur when using simulated array lengths similar to those found with clinical devices. Furthermore, unilateral spectral compression was found to have a graded effect on binaural fusion. Additionally, when one ear received a vocoded signal and the other ear received an unprocessed signal, there was little to no binaural fusion, regardless of whether or not there was also spectral compression. These results provide further evidence that unilateral spectral compression may detrimentally affect SSD patients.

There are some differences between the simulated arrays and what would actually occur in patients with a cochlear implant. Typically, the acoustic filters range from approximately 0.2–7 kHz (a smaller range than in this experiment) and the most basal electrode will stimulate the tonotopic location that corresponds to over 10 kHz (higher frequency than the most basal simulated channel in this experiment). That means that the mismatch between the acoustic and electric ears for SSD will likely be more extreme than that used in this experiment, although adaptation over time may effectively perceptually reduce that mismatch (Reiss et al. 2008; Reiss et al. 2011).

One of the largest effects in the current study was the difference between when the signal for both ears were unprocessed and when the signal for one ear was unprocessed and that for the other ear was vocoded. In those conditions, perception changed from nearly always fused to nearly never fused. This suggests that combining a vocoded and non-vocoded ear can be very detrimental to binaural abilities. Although there are clear qualitative differences in the sound presented to the two ears, the breakdown of fusion may also reflect dynamically changing mismatches between the two ears since for the vocoded stimuli all frequencies within a given analysis filter are mapped onto the same center frequency. This would essentially create a spectral mismatch between ears that varies in magnitude as the spectral characteristics change throughout the speech utterance.

The 20mm and 17mm conditions were spectrally compressed relative to the Tonotopic Matched condition. In contrast, when paired with the 23mm condition, it is the Tonotopic Matched stimulus that is spectrally compressed. Despite these differences, the 20mm, 17mm, and 23mm conditions all appear to fall along the same line characterizing the differences between the (unsigned) average mismatch between ears in mm and percent fusion. In other words, the mismatch in mm seems to be the critical factor rather than how it relates to a tonotopic match between the analysis and carrier filters. From the current data it is not clear if average mm is the key metric. Using the peak mismatch would have the same strong relationship with percent fusion since peak and average mismatch change in a correlated manner with these stimuli. Other mismatch manipulations, such as an overall shift instead of a compression would be needed to isolate the relevant metric.

Although in the current experiment the simulated array length was manipulated, differing amounts of spectral mismatch can also result from the considerable variability in cochlear duct length. For example, histological studies have indicated that the cochlear duct length can vary from approximately 25 to 35mm (Hardy 1938; Lee et al. 2010). As such, minimizing spectral mismatch across ears may require matching the array length to the cochlear duct length.

General Discussion

The results from experiment one indicated that both unilateral spectral compression and unilateral temporal compression can prevent binaural fusion. The amount of temporal compression was comparable to what would occur for some SSD patients because it was based on the removal of the traveling wave delay. However, the amount of spectral compression was large compared to what would likely occur with SSD patients since it

simulated compression onto an 11.6mm array, considerably shorter than what would typically be used, resulting in an average 4.3mm mismatch across ears. Experiment 2 used more typical array lengths of 17–23mm (1.1mm expansion to 1.9mm compression) and found that binaural fusion was still reduced, although the effect was graded and was related to the average mismatch in mm across ears (regardless of whether or not it was the ear that delivered signals to the tonotopically correct location that was relatively spectrally compressed). Additionally, combining an ear receiving an unprocessed signal with one receiving a vocoded signal resulted in virtually no binaural fusion. Together, these results suggest that the similarity of the signals at the two ears is key to whether or not binaural fusion occurs, although it is not clear what the relationship is between orthogonal dimensions such as spectral and temporal similarity.

Both unilateral spectral and temporal compression could potentially be addressed. Spectral compression could be compensated for by changing the analysis filters on the processors. However, doing so may result in the analysis filters covering a smaller frequency region, which might also result in reduced unilateral performance. Alternatively, unilateral spectral compression can be minimized by choosing an array length based on an individuals' cochlear duct length. Additionally, a channel-specific delay could be implemented to mimic the naturally occurring traveling wave delay, such as by using a gammatone filterbank for the time to frequency analysis. Adding channel-specific delays has been shown to improve unilateral performance (Taft et al. 2010).

In conclusion, unilateral spectral and temporal compression both reduce binaural fusion. This may be an underlying factor in the slow development of binaural abilities for SSD patients with a cochlear implant in one ear. Additionally, the detrimental effects of unilateral spectral compression also likely detrimentally affects patients with different length arrays in each ear, resulting from the use of different array designs or because electrodes are deactivated in one ear. By making changes to the processors and fitting algorithms it may be possible to improve these patients' binaural abilities.

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List of abbreviations

SSD	single sided deafness
ANOVA	analysis of variance

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- Normal hearing listeners' binaural fusion was tested using vocoded speech
- Binaural fusion was reduced if spectral compression was added to one ear
- Binaural fusion was also reduced if temporal compression was added to one ear
- Unilateral spectral and temporal compression may hinder patients' binaural fusion

Figure 1. Schematic illustration of the conditions for Experiment 1 showing the relative time and center frequency for each vocoded condition (color online).

Figure 2.

The effect of spectral and temporal compression on binaural fusion. Bars indicate 20% trimmed means and error bars indicate the winsorized standard error.

Figure 3. Schematic illustration of the conditions for Experiment 2 showing the amount of spectral compression for various simulated array lengths. This reflects a cochlear duct length of approximately 35mm.

Figure 4.

The effect of spectral compression on binaural fusion when both ears are receiving vocoded signals. Bars indicate 20% trimmed means and error bars indicate the winsorized standard error.

Figure 5.

The relationship between the average mismatch between ears (in mm) and percent fusion. Each point represents the 20% trimmed mean for a given condition. The line indicates the fit based on a mixed effect regression.

Figure 6.

The effect of spectral compression on binaural fusion when one ear is receiving an unprocessed signal and the other ear is receiving a vocoded signals. Bars indicate 20% trimmed means and error bars indicate the winsorized standard error.