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Research paper

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 each 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.

1. Introduction

Cochlear implants provide considerable benefits for patients with bilateral deafness, often yielding dramatic improvements in localization, as well as better speech understanding in noise (Dunn et al., 2010, 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 26 mm, the input filters have default center frequencies that cover approximately 19 mm–23 mm 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.,

Abbreviations: SSD, single sided deafness; ANOVA, analysis of variance

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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.

2. 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.

2.1. Methods

2.1.1. Participants

Twelve normal hearing listeners participated in this experiment. All participants had pure tone thresholds ≤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 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.

2.1.3. 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.

2.1.4. Spectral and temporal manipulations

Three conditions were tested (see Fig. 1). As a baseline, participants were tested with the same signal sent to both ears (**Identical condition**). For the **Spectrally Compressed condition**, the filters for the narrowband carrier in one ear were equally spaced along the cochlea covering 1–7 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 **Temporally Compressed 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

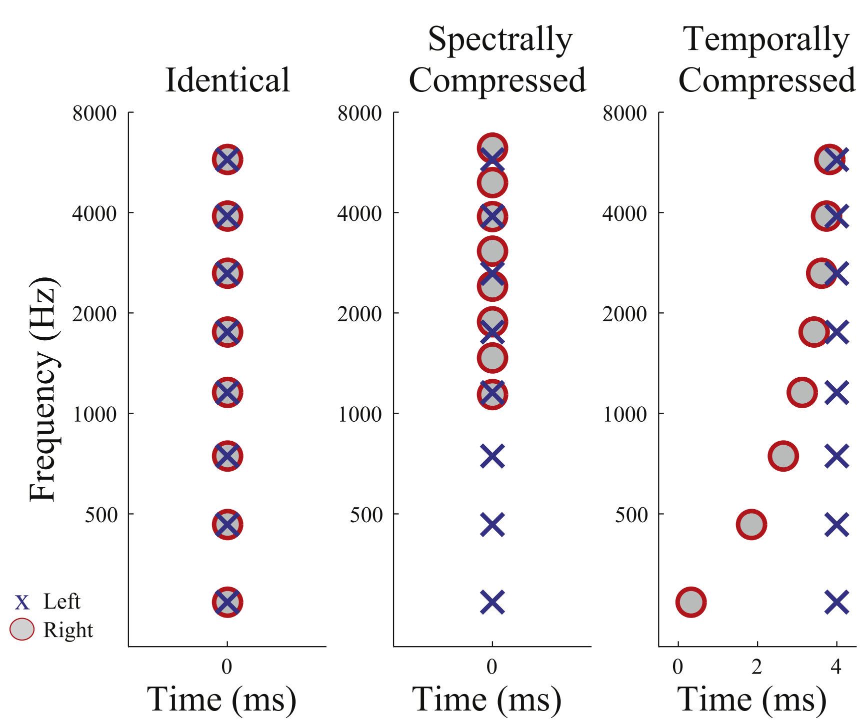

Fig. 1. Schematic illustration of the conditions for Experiment 1 showing the relative time and center frequency for each vocoded condition. (The reader is referred to the web version of this article for the color version of this figure.)