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Binaural Benefit with and without a Bilateral Spectral Mismatch in Acoustic Simulations of Cochlear Implant Processing

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Abstract

Objectives—This study investigated whether a spectral mismatch across ears influences the benefit of redundancy, squelch, and head shadow differently in speech perception using acoustic simulation of bilateral cochlear implant (CI) processing.

Design—Ten normal hearing subjects participated in the study, and acoustic simulations of CIs were used to test these subjects. Sentence recognition, presented unilaterally and bilaterally, was measured at +5 dB and +10 dB signal-to-noise ratios (SNRs) with bilaterally matched and mismatched conditions. Unilateral and bilateral CIs were simulated using 8-channel sine-wave vocoders. Binaural spectral mismatch was introduced by changing the relative simulated insertion depths across ears. Subjects were tested while listening with headphones; head-related transfer functions were applied before the vocoder processing to preserve natural interaural level and time differences.

Results—For both SNRs, greater and more consistent binaural benefit of squelch and redundancy occurred for the matched condition while binaural interference of squelch and redundancy occurred for the mismatched condition. However, significant binaural benefit of head shadow existed irrespective of spectral mismatches and SNRs.

Conclusions—The results suggest that bilateral spectral mismatch may have a negative impact on the binaural benefit of squelch and redundancy for bilateral CI users. The results also suggest that clinical mapping should be carefully administrated for bilateral CI users to minimize the difference in spectral patterns between the two CIs.

Keywords

binaural hearing; cochlear implant; spectral mismatch; speech perception; binaural benefit

Introduction

The evidence for the advantage of bilateral cochlear implants (CIs) over a unilateral CI in speech perception is well documented (Dunn et al. 2008; Mosnier et al. 2009; Muller et al. 2002; Schleich et al. 2004; Tyler et al. 2007; van Hoesel and Tyler 2003; Wackym et al. 2007; Yoon et al. 2011b). However, the amount of the binaural benefit, the positive difference between bilateral performance and the better-performing ear alone, varies

strongly between and within subjects (across ears) in terms of binaural hearing components such as squelch, redundancy, and head shadow. Variability between subjects who received the most and the least binaural benefit was approximately 45%, 30%, and 70% for squelch, redundancy, and head shadow, respectively (Buss et al. 2009). Variability among subjects who received significant benefit of squelch, redundancy, and head shadow was approximately 21%, 32%, and 64%, respectively (Eapen et al. 2009). Such high variability also exists within subjects (across ears). Litovsky et al. (2006) tested 34 bilateral CI users for sentence recognition using an adaptive procedure. Twenty-seven out of these 34 subjects exhibited a difference in the benefit from squelch larger than 2 dB across ears, and 31 out of 34 subjects had a largely different bilateral advantage conferred by head shadow across ears. Such high variability also remained over time. Eapen et al. (2009) assessed the stability of the binaural benefit of squelch and head shadow over time (up to 4 years) in 9 CI patients using sentence recognition in noise. They reported that the variability across ears (about 25%) in the benefit of squelch and head shadow remained consistent over four years.

It has been hypothesized that such high variability is due to differences across ears in pathological factors such as implantation method (sequentially or simultaneously), age at implantation, duration of profound deafness, or amount of bilateral experience. Zeitler et al. (2008) conducted a word and sentence perception test in noise and quiet with a large population of bilateral subjects (22 adults and 43 children with a minimum of 6 months between surgeries) to evaluate the correlation between binaural benefit and pathological factors. They showed that for both adults and children significant binaural benefit occurred regardless of time between implantations, length of deafness, or age at time of second implantation. For sentence recognition at +10 dB SNR, however, time between implantations and length of deafness did negatively, although weakly, influence performance. In addition, Mosnier et al. (2009) recruited 27 bilateral CI patients with relatively strict subject selection criteria. The selection criteria included similarities between the two ears in duration of profound hearing loss, etiology, duration of hearing aid experience, number of activated electrodes, stimulation rate, and comfort level. In addition, all patients had received both CIs (Med-El Combi 40+) in a simultaneous procedure. Both CIs were simultaneously activated, and the same speech coding strategy (continuous interleaved sampling) was used for both CIs. Subjects were tested for disyllabic word recognition preoperatively and postoperatively in noise. The masker was presented simultaneously from 5 loudspeakers at different locations including a central one (0° azimuth) that presented the speech target. They still observed a high variability in binaural benefit across subjects and ears. These results suggest that variability in binaural benefit is not directly related to pathological factors and parameters associated with processing strategies.

Monaural and binaural spectral mismatch caused by different insertion depths may be another reason for this high variability. Finley et al. (2008) measured insertion depths using computed tomographic images of the cochlea from 14 unilateral CI patients and related CNC word recognition scores in quiet with different insertion depths. Their correlation analyses showed that variability in word recognition scores across unilateral CI subjects is largely explained by variability in scalar location and insertion depth of the electrode array. Recently, Yoon et al. (2011a) simulated binaural spectral mismatch across ears using acoustic simulations with normal hearing listeners; they measured the benefit of binaural redundancy for sentence recognition in the context of bilateral CIs. Significant interference of binaural redundancy, negative difference between bilateral performance and the better performing ear alone, occurred in noise and in quiet when spectral mismatch between ears was more than 2 mm while significant benefit of binaural redundancy occurred in noise and in quiet when binaural spectral mismatch was less than 1mm. The results indicate that

subjects who receive similar and redundant speech information between implanted ears are likely to have a large benefit of binaural redundancy.

In current literature, there is enough evidence showing significant speech perception benefit in terms of head shadow, squelch, and redundancy with two CIs over unilateral CI in noise and quiet. However, substantial variability exists in the binaural benefit attributed to these three components of binaural hearing across and within subjects. It is known that such variability is poorly related to pathological factors and parameters associated with processing strategies; currently there is no clear explanation for such high variability. Results from a recent normal hearing study suggest that binaural spectral mismatch across ears may be one of the contributing factors to the high variability in the binaural benefit in CI listeners (Yoon et al., 2011a). However, the study of Yoon et al. (2011a) focused on the relationship between the benefit of binaural redundancy and spectral mismatch across ears. Thus, it still remains unclear how binaural benefit in terms of squelch and head shadow will be affected by the presentation of mismatched and matched speech information across ears. In the present study, we tested a hypothesis that if spectral mismatch generated by different insertion depths across ears affects the amount of binaural benefit, then it is likely that spectral mismatch contributes to the variability of binaural benefit in terms of head shadow, squelch, and redundancy effects using acoustic simulations of bilateral CI processors.

Materials and Methods

Subjects

Ten normal-hearing subjects (6 females and 4 males) participated in the study. Subjects were native speakers of American English and between 21 to 55 years old. All had thresholds better than 20 dB HL at audiometric frequencies from .25 to 8 kHz. All subjects provided informed consent, and all procedures were approved by the local Institutional Review Board.

Stimuli

Sentence recognition was measured at signal-to-noise ratios (SNRs): +5 dB and +10 dB using IEEE sentences (Rothauser et al. 1969). According to the findings of the Yoon et al (2011a) study, these two SNRs were selected to avoid floor and ceiling effects. The steady-state speech-shaped noise masker (1000-Hz low-pass cutoff frequency, -12 dB/oct) was used to have a generic long-term speech spectrum. The SNR was calculated in terms of the long-term RMS of the speech signal and noise. Speech and noise were mixed at the target SNR, and the combined signal and noise was then scaled to 65-dB (A) sound pressure level (Fluke True RMS voltmeter). Head-related transfer functions (HRTFs) (Gardner and Martin 1994) were applied to both speech and noise separately before the vocoding processing to preserve natural interaural level and timing differences. The target-to-mixing ratio after HRTF filtering was within 1 dB deviation from the initial SNRs (+5 dB and +10 dB). For example, when noise was presented from the front (noise front, NF), the actual target-to-mix ratio in both ears was 4~6 dB for the +5 dB SNR and 9~11 dB for the +10 dB SNR. When the noise was presented from left (noise left, NL), right ear had approximately 6.5 dB SNR benefit due to head shadow effect (+11.5 dB for +5 dB SNR and +16.5 dB for +10 dB SNR). The same amount of dB SNR benefit was provided for the left ear when the noise was presented from right (noise right, NR). Speech was always presented from the front; noise was presented from NF, NR, or NL. The speech and noise was then mixed for the further vocoding processing.

Signal processing

The acoustic 8-channel sine-wave vocoders that generated the spectrally shifted speech stimuli due to the different insertion depths between ears were constructed as follows. The input acoustic signal was band-pass filtered into eight frequency bands using 4th-order Butterworth filters. The attenuation at the crossover point of adjacent filter bands was -3 dB. A fixed input frequency range (200–7000 Hz) was used for the analysis bands in all different insertion depths so that spectral information embedded above 6000 Hz for consonant recognition could be covered. The corner frequencies of each band and tonotopic locations were determined by the Greenwood function (1990) with a 35-mm-long cochlea. The temporal envelope in each band was extracted by half-wave rectification and low-pass filtering (fourth-order Butterworth: -24 dB/oct) with a 160-Hz cutoff frequency. The envelope of each band was used to modulate a sinusoid with frequency matching the center frequency of the carrier band. The output carrier bands were upwardly shifted to simulate different insertion depths of a 16-mm-long (i.e., the length of a typical electrode array for Nucleus, AB HR90K, and Med El Sonata or Pulsar medium), 8-electrode array with 2-mm electrode spacing; the spectral envelope was compressed. Spectral mismatch was accomplished by shifting the sine carrier bands linearly toward the base on 22 mm (8-mm shift from the analysis bands) and 25 mm (5-mm shift from the analysis bands), relative to fixed analysis bands. The 25-mm insertion depth was selected as a reference because the recommended insertion depth for the commercialized cochlear implant devices is about 24 ~ 25 mm so the electrode array is positioned at the middle of the cochlea (assuming that the total length of cochlear is 35mm and the length of electrode array is 16mm). The selection of the 22-mm insertion depth was made on the basis of the results of our previous study (Yoon et al. 2011a); binaural redundancy interference occurred when insertion depths was simulated with 22 mm to the base. Another reason to test the 22-mm shift is based on the results of a previous study (Li and Fu, 2007) showing that speech patterns were not learned if the monaural tonotopic mismatch was larger than 8 mm. The details of this acoustic simulation are summarized in Table 1.

Note that sine-wave vocoders, rather than noise-band vocoders, were used to restrict the place of stimulation for each channel within the cochlea so that the effect of spread of excitation would be minimized. In addition, it should be noted that while the spectral envelope from the frequency range of analysis bands was compressed onto the frequency range of carrier bands, compression was uniform across the different insertion depths. Thus, the spatial patterns within the cochlea were similar across conditions but were delivered to different cochlear regions. Also, within each different insertion depth, there were different degrees of spectral mismatch for different frequency regions of the acoustic input due to spectral compression.

Procedure

All testing was conducted under three listening conditions: left ear alone with 25-mm insertion depth (L25), right ear alone with either 22-mm (R22) or 25-mm (R25) insertion depth, and both ears (L25+R22 or L25+R25) for each location of noise masker, NF, NR, and NL. To familiarize the subjects with sine-vocoded stimuli, four subjects who had no prior listening experience were provided 30 minutes of familiarization with both matched (L25 with IEEE list 1) and shifted (R22 with list 2 and L25+R22 with list 3) conditions before the formal test. Subjects' asymptote was reached by this 30-minute familiarization at each listening condition. Familiarization was not provided for another six subjects who had more than three hours of prior experience with vocoded speech. Stimuli lists used for familiarization (lists 1~3) were excluded from the formal test. Hence, a total of 69 IEEE sentence lists were used out of 72 lists.

After the vocoder processing, the output signal was delivered via an audio interface (Edirol UA 25) to headphones (Sennheiser HDA 200) in a double-walled sound-treated booth (IAC). During testing, a sentence list (out of 69, excluding 3 lists used for familiarization) was randomly selected, and sentences were randomly selected from within the list (without replacement) and presented to the subject, who was instructed to repeat the sentence as accurately as possible. Subjects were instructed to guess if they were not sure. No training or trial-by-trial feedback was provided during the formal testing. The performance scores for words correctly identified in each sentence were obtained for each condition over 2 separate runs with a different list of sentences (total 20 sentences presented) at each SNR. All experimental conditions (Listening conditions: left, right, and both; Insertion depths: R22 and R25; SNR: +10 dB and +5 dB; Location of noise masker: NF, NR, and NL) were randomized and counterbalanced across subjects; subjects never heard the same sentence list twice for any experimental conditions.

Throughout this article, head shadow effect is defined as the difference between the percent correct obtained in a unilateral listening condition with noise presented to the ipsilateral implant compared with the percent correct in bilateral listening condition with noise presented to the same side of CI for unilateral listening (Litovsky et al. 2006). As such, two estimates of head shadow can be computed: Head shadow for the left ear = NR (bilateral) – NR (right CI only) or head shadow for the right ear = NL (bilateral) – NL (left CI only). Squelch effect is defined in terms of the advantage associated with bilateral listening when compared with the shadowed ear alone (Litovsky et al. 2006): Squelch for the left ear = NL (bilateral) – NL (right CI only) or squelch for the right ear = NR (bilateral) – NR (left CI only). Binaural redundancy is the advantage associated with bilateral listening when compared with either ear alone when both ears receive the same signal (Litovsky et al. 2006): Redundancy = NF (bilateral) – NF (better performing CI only).

Results

Figure 1 shows mean recognition scores for unilateral and bilateral listening conditions as a function of masker location with SNR as a parameter. In the mismatched condition (L25+R22) at +5dB SNR (Fig. 1, top-left panel), binaural interference was evident for NF and NR. Two-way repeated-measures analyses of variance were performed, with masker locations (NF, NR, and NL) and listening condition (R22, L25 and L25+R22) as factors and test run as the repeated measure. A significant effect of masker location ($F(2,36)=65.8$, $p<0.001$) and of listening condition ($F(2,36)=58.6$, $p<0.001$) was found. A significant interaction between two main effects existed as well ($F(4,36)=44.2$, $p<0.001$). Post-hoc pair-wise comparisons (Holm-Sidak method) showed significant binaural interference for NR, as indicated by a plus symbol, but significant binaural benefit occurred for NL, as indicated by asterisks.

Similarly, in the mismatched condition at +10 dB SNR (Fig. 1, top-right panel), binaural interference occurred for NF and NR. Two-way repeated-measures analyses of variance showed significant main effect of masker location ($F(2,36)=18.0$, $p<0.001$) and of listening condition ($F(2,36)=141.8$, $p<0.001$). Interaction was also significant ($F(4,36)=29.8$, $p<0.001$). Post-hoc pair-wise comparisons (Holm-Sidak method) showed significant binaural interference for NF ($p<0.05$), but significant binaural benefit for NL ($p<0.05$).

The two bottom panels of Fig. 1 present the performance for the matched condition (L25+R25). The binaural performance was higher than that with the better ear alone at +5dB SNR (bottom-left panel) regardless of masker location. Two-way repeated-measures analyses of variance showed significant effect of masker location ($F(2,36)=15.8$, $p<0.001$) and of listening condition ($F(2,36)=45.7$, $p<0.001$). Interaction was also significant

($F(4,36)=70.8, p<0.001$). Post-hoc pair-wise comparisons (Holm-Sidak method) showed that binaural performance (L25+R25) is significantly better than with the better performing ear alone (R25) for NF, as indicated by asterisk ($p<0.05$).

Similarly, binaural performance at +10 dB SNR for the matched condition (Fig. 1, bottom-right panel) was constantly better than that of the better performing ear alone. Two-way repeated-measures analyses of variance showed significant effect of masker location ($F(2,36)=15.8, p<0.001$) and listening condition ($F(2,36)=90.7, p<0.05$) along with significant interaction ($F(4,36)=70.8, p<0.001$). Post-hoc pair-wise comparisons (Holm-Sidak method) showed that binaural performance is significantly higher than the better performing ear alone, regardless of masker location, as indicated by asterisk ($p<0.05$).

Figure 2 presents mean binaural benefit in terms of head shadow (top panel), squelch (middle panel), and redundancy (bottom panel). The binaural benefit of head shadow was statistically significant for all conditions, as indicated by asterisks. For the mismatched condition, the benefit of head shadow for the right ear was 18% and 10% at +5 and +10 dB SNRs and for the left ear 40% and 50% at +5 and +10 dB SNRs. For the matched condition, the benefit of head shadow was similar (about 40%) for both ears regardless of SNRs and masker locations. Three-way analyses of variance showed significant effect of listening condition ($F(1,72)=24.54, p<0.001$) and head shadow for each ear ($F(1,72)=61.48, p<0.001$), but not of SNR ($F(1,72)=0.06, p>0.05$). Pair-wise multiple comparisons (Holm-Sidak method) showed that the difference between the benefit of head shadow for the left and right ears was significant ($p<0.05$) for the mismatched condition but not for the matched condition ($p>0.05$). The comparisons also showed that head shadow was significantly different between the mismatched and the matched conditions ($p<0.05$) for the right ear, but not ($p>0.05$) for the left ear.

The middle panel of Fig. 2 shows the average binaural benefit of squelch. For the mismatched condition (L25+R22), the benefit of squelch was negative for the right ear at both SNRs (significant at +5 dB SNR, as indicated by a plus symbol) while there was significant benefit of squelch for the left ear at both SNRs, as indicated by an asterisk. In contrast, for the matched condition (L25+R25) the benefit of squelch for both ears was positive at both SNRs (significant at +10 dB SNR, as indicated by an asterisk). Three-way analyses of variance showed significant effect of the squelch for each ear ($F(1,72)=14.4, p<0.001$), but not of listening condition ($F(1,72)=1.94, p>0.05$) and SNR ($F(1,72)=2.8, p>0.05$). Pair-wise multiple comparisons (Holm-Sidak method) showed that the difference in the benefit of squelch across ears was significant ($p<0.05$) for the mismatched condition but not for the matched condition ($p>0.05$). Comparisons also showed significant differences in the squelch effect between the mismatched and the matched conditions for the right ear at both SNRs ($p<0.05$), but not for the left ear ($p>0.05$).

The analysis of the redundancy effect (Fig. 2, bottom panel) showed binaural interference for the mismatched condition (L25+R22) at both SNRs (significant at +10 dB SNR, as indicated by a plus sign) while a significant benefit was observed for the matched condition (L25+R25) at both SNRs, as indicated by asterisk ($p<0.05$). Two-way analysis of variance showed a significant effect of listening condition ($F(1,36)=20.3, p<0.001$), but not of SNR ($F(1,36)=0.004, p>0.05$). Pairwise multiple comparisons (Holm-Sidak method) showed that the difference between the mismatched and matched conditions was significant ($p<0.05$) at both SNRs.

Discussion

The results show that the binaural benefit of squelch, redundancy, and head shadow was consistently greater for the spectrally matched condition across ears compared to those for the mismatched condition regardless of masker locations and SNRs. For the mismatched condition, the binaural interference of squelch was introduced at both SNRs when the poorer ear was added. The binaural interference of redundancy was also introduced at both SNRs for the mismatched condition.

In the mismatched condition (L25+R22) at both SNRs (Fig. 2, top panel), the magnitude of the head shadow for the right ear (R22) is relatively small (about 10~15% benefit), compared to that (40%~55%) of the head shadow for the left ear (L25). That is, the benefit of head shadow is small when the noise masker was presented to the better ear (L25), compared to when the noise masker was nearer to the poorer ear (R22). These results suggest that the poorer ear was not fully advantaged by the head shadow effect, while the better ear was clearly influenced. Similar findings were reported by Litovsky et al. (2006), who measured the binaural benefit of the head shadow from 37 simultaneously implanted subjects for sentence recognition in noise. They found that the benefit of head shadow is greater in the asymmetry group when the noise was near the poorer ear than when the masker was presented to the better ear.

Binaural interference of squelch occurred at both SNRs for the right ear (Fig 2. middle panel) in the mismatched condition. Specifically, binaural performance was about 10 percentage points poorer than performance with the better ear alone when noise was presented to the poorer ear alone. This means that when the poorer ear was added to the better ear, distorted speech information was actually added to the better ear; integration of the speech information failed, leading to the binaural interference. This idea was supported by a study of Li and Fu (2007). They showed with acoustic simulation that vowel patterns were not learned if the tonotopic mismatch was larger than 8 mm; large-spectrally shifted vowels were perceived as noisy information rather than actual speech patterns. In the present study, speech information processed with R22 (8-mm monaural shift) might be perceived as highly smeared speech information (like a noise masker) rather than actual speech information.

In contrast to the binaural interference of the squelch for the right ear in the mismatched condition, there was significant benefit of squelch for the left ear at both SNRs when noise was presented to the better ear (Fig 2. middle panel). This benefit conferred by squelch can be explained by integration of speech information processed each ear. That is, when the noise source was nearer to the better ear, the better ear can still tolerate the level of the masker and process some speech cues. At the same time, SNR improved for the poorer ear due to a head shadow (NL). This situation provides similar speech information at both ears (the difference in performance between L25 and R22 is less than 10%), leading to an integration process. Consequently, binaural benefit of squelch occurred for the left ear. This is consistent with findings of Litovsky et al. (2006), who showed that the benefit of squelch for subjects with asymmetric performance across ears was larger when the noise source was nearer the better ear.

When noise was presented from front for the mismatched condition, binaural interference of redundancy occurred at both SNRs (Fig. 2, bottom panel). This result suggests that the redundancy mechanism failed to fuse speech information due to severe spectral mismatch between analysis bands and carrier bands in the poorer ear. A similar observation was reported in the study of Litovsky et al. (2006) who showed that none of 10 asymmetric

bilateral CI users showed significant binaural benefit of redundancy in sentence recognition under babble noise.

The occurrence of the binaural interference in the binaural redundancy for the mismatched condition is not uncommon. Litovsky *et al.* (2006) tested two groups of bilateral CI users: asymmetric subjects (a difference in speech reception threshold (SRT) between ears > 3.1 dB, $n=10$) and symmetric subjects (difference in SRT between ears < 3.1 dB, $n=24$). They reported that none of asymmetric subjects showed significant binaural benefit with binaural interference for some subjects even though all of the symmetric subjects showed significant binaural benefit over the better performing ear alone. Mosnier *et al.* (2009) also showed that bilateral CI users with asymmetrical monaural speech scores in each ear (greater than 20 percentage points) received no binaural benefit. Furthermore, Siciliano *et al.* (2010) in normal hearing listeners reported a severe binaural interference when interleaved shifted bands (1, 3, 5 bands with 6-mm upward shift) on one ear were presented together with the unshifted bands (2, 4, 6 bands on other ear). Performance with these combinations never exceeded that with the unshifted bands alone in sentence and vowel recognition (particularly F1 information transmission) in quiet. Recently, Yoon *et al.* (2011a) also demonstrated using acoustic simulation that binaural interference occurred when the difference in insertion depth was basally 2-mm or larger. These results suggest that integrating spectrally-mismatched speech information across the ears is not overly successful. The reasons for the asymmetrical performance obtained in some patients remain to be investigated. A possible explanation could be variations in the neural survival rate or small differences in the electrode position and location (tympani or vestibule) in the cochlea, with lack of adjustment of speech coding strategy. Unilateral mapping for bilateral CI users might be an issue as well. For example, Dorman *et al.* (1997) and Baskent and Shannon (2003) showed with acoustic simulation that the apical shift smaller than 0.25 octaves did not significantly decrease sentence recognition scores. Goupell *et al.* (2008) also showed for both CI and NH groups that varying the number of channels by the two caused no significant decrease in speech understanding performance compared to the nearest matched condition when the upper-frequency boundary was shifted by no more than 0.77 octaves. In the present study, the binaural interference is 4 and 8 percentage points at +5 dB and +10 dB SNRs while in the study of Yoon *et al.* (2011a) there is approximately 15 percentage points lower for the binaural condition than for the better ear alone at +5 dB SNR and in quiet. This discrepancy might be due to the difference in spectral resolution between the two studies (8 channel for the present study and 6 channel vocoders for the Yoon *et al.* (2011a) study).

Taken together, the binaural benefit attributed to head shadow, squelch, and redundancy is clearly influenced by the spectral mismatch between the ears. This result suggests that the lack of the binaural benefit in many bilateral CI users could be due to different insertion depths across the ears. This result also suggests that clinical mapping should be carefully administrated so that the differences in the pattern of spectral information across the ears can be minimized, resulting in the greater and consistent binaural benefit in noise. At present, the only way to see the differences in insertion depth between the ears is with multi-detector computed tomography imaging displaying the electrode placement as well as the relative electrode placement across the ears. Further postoperative electrode migration could also be an issue.

One of the limitations of the current study is the listeners' adaptation to the different degrees of spectral shift in each ear. Despite the fact that our subjects were provided 30-minutes of familiarization or 3-hours of prior listening experience to vocoded speech, it is possible that our subjects might be able to combine spectral cues from the two ears exposed for a longer period of time. However, Siciliano *et al.* (2010) showed that 10 hours of training with spectrally shifted sentences provided no binaural benefit in an acoustic simulation study. In

addition, many bilateral CI users do not show a binaural benefit in speech perception over the better ear alone in quiet and noise even after multiple years of bilateral use (Mosnier et al. 2009; Yoon et al. 2011b).

Another issue that might be confounded in the result of the present study is smoothing filter cutoff. A 160-Hz cutoff was used because previous studies showed no significant change in speech performance for envelope fluctuations between 50 Hz and 500 Hz in noise-band vocoder (Drullman et al. 1994; Shannon et al. 1995). However, the more recent study (Souza and Rosen, 2009) showed a strong effect of the envelope cutoff-frequency, particularly for sine-wave vocoder used for the present study. They compared speech recognition scores (consonants, vowels, and sentences) processed by sine-wave and noise-excited vocoder with 30 Hz and 300 Hz filter cutoff as a function of number of channel (from 2 to 5 channels). With a 30-Hz cutoff, the performance was better for noise-vocoding than for sine-vocoding. With a 300-Hz cutoff, the performance was better for sine-vocoding. It thus is possible that temporal envelope filtered with 160-Hz cutoff can transmit voicing cues, helping identify some of consonants.

It also should be noted that the binaural spectral mismatch between the ears influences the ability of bilateral CI users to utilize interaural time difference (ITD) cues. Because there is considerable variability across CI patients in terms of insertion depth (Aschendorff et al. 2005; Marsh et al. 1993) and neural survival across the ears (Fayad et al. 1991), it is very likely that interaural place mismatches are common, given current clinical fitting procedures. The ITD sensitivity of bilateral CI users has been shown to decrease with increasing place mismatch within single bilateral channels (Long et al. 2003; Poon et al. 2009; van Hoesel and Clark 1997). Poon et al. (2009) found that just-noticeable differences for ITDs can decrease by as much as 40 μ s between place-matched and place-mismatched bilateral channels. These results suggest that the binaural spectral mismatch influences not only spectral integration, but also temporal integration. This effect of the bilateral spectral mismatch on the ITD sensitivity for bilateral CI users is currently under investigation.

Finally, more restricted interpretation for the results of the present study is needed because the acoustic simulation of CI processing has a couple of limitations: smaller dynamic range for CI users than for normal hearing listener, poorer ability of CI users to process modulation and discriminate changes in modulation rate than that of normal hearing listeners, and presence of sideband information in simulation that are absent in CI processing (Stone et al., 2008). Another issue of acoustic simulation is related to the transmission of ITD particularly at lower frequencies. In electric hearing (clinical processors based on continuous interleaved sampling strategy), the ITDs are preserved in the envelopes only but in acoustic simulation ITDs are preserved both in the carriers (lower frequencies) and in the envelopes (modulations and/or higher frequencies). This issue becomes more serious because it is known that in normal hearing, the binaural carrier match is crucial for the carrier-ITD sensitivity (Henning, 1974) while a mismatch as great as several octaves is tolerable for the envelope-ITD sensitivity (Blanks et al., 2007). Thus, it is not clear how the carrier-ITD sensitivity in acoustic simulation influences the binaural benefit in speech perception.

Conclusions

The aim of the present study was to investigate whether the spectral mismatch across the ears influences the binaural benefit in head shadow, squelch, and redundancy differently for sentence recognition using acoustic simulation. The results showed that head shadow is the most prominent effect irrespective of the spectral mismatch even though the magnitude of the benefit was relatively small when the noise masker was nearer to the better ear for the

mismatched condition. The binaural benefit of squelch reliably occurred for the matched condition regardless of SNRs and masker locations. In contrast, for the mismatched condition binaural interference of squelch occurred when the noise masker was nearer to the poorer ear while a significant benefit of squelch occurred when the noise masker was nearer to the better ear. The results also showed the significant binaural benefit of redundancy for the matched condition at both SNRs while the binaural interference of redundancy for the mismatched condition at both SNRs. The results suggest that the bilateral spectral mismatch may have a negative impact on the binaural benefits of squelch and redundancy for bilateral CI users. These results also suggest that clinical mapping should be administrated for bilateral CI users in a manner that minimizes the difference of spectral patterns between two CIs.

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Short Summary

This study investigated whether bilateral spectral mismatch across ears influences the binaural benefit of redundancy, squelch, and head shadow differently in bilateral cochlear implant (CI) listening. Ten normal hearing subjects were unilaterally and bilaterally tested using acoustic CI simulations for sentence recognition in noise with bilaterally matched and mismatched conditions. Greater and more consistent binaural benefit of squelch and redundancy occurred for the matched condition while binaural interference occurred for the mismatched condition. The results suggest that spectral mismatch across ears may have a negative impact on the binaural benefit of squelch and redundancy for bilateral CI users.

Figure 1.

Mean recognition scores with standard error for each noise location and for listening conditions. Top panels present data for the mismatched condition, while the bottom panels do for the matched condition. Left and right ear is denoted by L and R, followed by insertion depths. NF means that noise was presented from front; NL and NR mean that noise was presented from the left (-90°) and the right ($+90^\circ$). Data is shown for both ears (dotted line), the left ear with 25mm insertion depth alone (filled circle), and the right ear with 22mm or 25mm insertion depth alone (open circle). Significant binaural benefit and interference are denoted by asterisks and plus signs. Data points for L25 shown in the both top and bottom panels are the same at each SNR.

Figure 2.

Mean binaural benefit for the matched and the unmatched conditions in terms of head shadow (top panel), squelch (middle panel), and redundancy (bottom panel). Significant binaural benefit and interference are denoted by asterisks and plus symbols. The error bars show standard error of the mean.

Table 1

Detailed parameters that used in the design for an 8-band analysis and carrier vocoder. Spectral mismatch was accomplished by shifting the sine carrier bands linearly toward the base to 22 mm and 25mm, relative to fixed analysis bands.

	Analysis bands	Carrier bands	
Insertion depth	29.7 mm	25 mm	22 mm
# of channel	8		
Corner frequencies [Hz]	200	513	851
	359	722	1168
	591	998	1586
	930	1363	2138
	1426	1843	2864
	2149	2476	3822
	3205	3310	5085
	4748	4410	6750
	7000	5860	8944
Length of electrode array	22 mm	16 mm	
Linear spacing between electrodes	2.75 mm	2.00 mm	
Filter slope [dB/oct]	24		
Carrier type		Sine wave	
Presentation level	65 dB (A) SPL		