Interaural spectral asymmetry and sensitivity to interaural time differences

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Abstract: Listeners' ability to discriminate interaural time difference (ITD) changes in low-frequency noise was determined as a function of differences in the noise spectra delivered to each ear. An ITD was applied to Gaussian noise, which was bandpass filtered using identical high-pass, but different low-pass cutoff frequencies across ears. Thus, one frequency region was dichotic, and a higher-frequency region monotic. ITD thresholds increased as bandwidth to one ear (i.e., monotic bandwidth) increased, despite the fact that the region of interaural spectral overlap remained constant. Results suggest that listeners can process ITD differences when the spectra at two ears are moderately different.

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1. Introduction

Cochlear implant (CI) patients who retain some residual low-frequency hearing (either in the implanted or in the unimplanted ear) often can combine the two sources of stimulation to show improved speech intelligibility in a competing background over implant-only performance (Brown and Bacon, 2009; Gifford *et al.*, 2010). In some cases the patient may have residual low-frequency hearing in both the implanted and the unimplanted ears, and as such one might consider stimulating both ears acoustically to take advantage of interaural time differences (ITDs) to improve speech intelligibility. There are very few data on the availability of ITDs in the low-frequency acoustic region that might improve speech intelligibility for CI patients with bilateral residual hearing. Brown and Bacon (2007) simulated such a configuration by vocoding a target-plus-background mixture and presenting it to the left ear (thus simulating a single cochlear implant), and low-pass filtering the same mixture at 500 Hz, and presenting it to both ears (simulating low-frequency residual hearing in both ears). They found that applying an ITD of 600 μs to the 500-Hz low-pass background noise improved speech intelligibility by as much as 20 percentage points over performance when the background ITD was 0 μs.

For many CI listeners with bilateral residual acoustic hearing, the audiometric configurations in the low-frequency region will be asymmetrical. That is, they may have more hearing in one ear than the other, both in terms of thresholds and frequency extent. This paper is concerned with the relationship between ITD sensitivity and asymmetry in the degree of spectral overlap between the two ears. We investigated ITD discrimination thresholds as a function of the spectral overlap of low frequency noise in one ear relative to that in the other ear. This paper is similar to the recent work of Francart and Wouters (2007) who investigated a similar question of spectral overlap, only in their case for interaural level differences (ILDs). In the current study we were interested in how the ability to process ITDs changes as the spectrum of a

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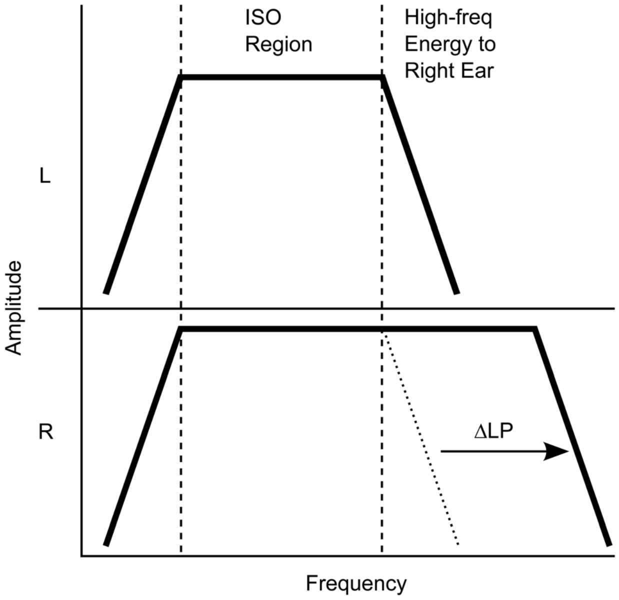

Fig. 1. Schematic depicting the relationship of the noise spectra at the left (top row) and right (bottom row) ears used. The two vertical dashed lines encompass the ISO region, which is the spectral region that is present at both ears. The arrow represents the change to the stimuli that occurred due to the manipulation of interest, and the dotted plot represents the starting point of the manipulation. The low-pass cutoff frequency of the band of noise delivered to the right ear was initially the same as that for the left ear, and was systematically increased in frequency.

low-frequency sound delivered to one ear varies in the amount of spectral overlap with the spectrum presented to the other ear.

Figure 1 depicts the spectral overlap manipulation used in the current study. The stimulus was a bandpass-filtered Gaussian white noise, delivered to both ears with an ITD. The manipulation was to systematically increase the upper (low-pass) cutoff frequency of the band of noise in the right ear. This manipulation was designed to simulate varying asymmetries of loss in the low-frequency region. Note that the amount of interaural spectral overlap (ISO) is held constant, and there is a monotic, high frequency band in the right ear. It is the width of this monotic band that was varied systematically.

2. Methods

2.1 Listeners

Five listeners with normal hearing participated in the experiment. Listener 1 was the author C.A.B. All procedures were approved by the institutional review board at ASU.

2.2 Stimuli

All stimuli were 200-ms Gaussian noise bursts shaped with 10-ms raised cosine rise-decay times. For a given interval, the same noise burst was used to generate the stimuli presented to both ears, and the overall level of the noise was randomly varied between 86–90 dB SPL. The noise delivered to the left ear was high-pass filtered at 50 Hz, and low-pass filtered at either 125 or 250 Hz. For the noise delivered to right ear, the high-pass cutoff frequency was 50 Hz, and the low-pass cutoff frequency was varied to produce differences in low-pass cutoff frequencies (ΔLP) between the two ears of between 0 (the same ΔLP in both ears) and 2 octaves, in 1/3-octave steps. See Table 1 for filter cutoffs. The goal was to simulate varying degrees of symmetrical and asymmetrical

Table 1. Low-pass filter cutoff frequencies, in Hz, for each ear, in each condition used. Values in the column labeled "ΔLP" are the differences in cutoff frequency across the ears, expressed in octaves.

Condition	ΔLP (Oct)	Low-pass cutoffs (Hz) Left ear	Right ear
1	0	125	125
2	2/6	125	157
3	4/6	125	198
4	6/6	125	250
5	8/6	125	315
6	10/6	125	397
7	12/6	125	500
8	0	250	250
9	2/6	250	315
10	4/6	250	397
11	6/6	250	500
12	8/6	250	630
13	10/6	250	794
14	12/6	250	1000

low-frequency hearing loss. With respect to spectral overlap, the manipulation resulted in an ISO region that remained fixed in width while the width of a monotic high-frequency region was increased. The ITDs were whole waveform ITDs in which the entire waveform in one ear was time shifted relative to that in the other ear.

2.3 Equipment and procedure

Listeners were seated in a double-walled sound booth, and used Sennheiser HD250 headphones. Stimuli were created digitally, and converted to analog signals using an Echo Audio Gina 3G sound card. An adaptive, two-interval, two-alternative force-choice (2AFC) paradigm was employed, with the tracking variable being ITD. The initial ITD was 500 μs, and step sizes were 50 μs for the first two reversals and 20 μs for the last six reversals (thus, runs were eight reversals long). The noise in one interval contained an ITD favoring the left ear equal to one-half the nominal ITD, and the other interval contained one-half the nominal ITD favoring the right ear. For example, if the track called for a 300 μs ITD, then an ITD of 150 μs (half the ITD) was applied to the left-leading interval, and a 150-μs ITD was applied to the right-leading interval. The interval containing the left-leading ITD was randomly determined and the listeners' task was to indicate which interval was perceived to be more to the left. A two-down, one-up adaptive tracking procedure (tracking the 70.7% correct point on the psychometric function) was used to estimate ITD thresholds. No trial-by-trial feedback was provided. Thresholds were based on the average of the ITD values at the last 6 reversals. At least three such thresholds were used to estimate the final ITD threshold for a given subject in a given condition.

3. Results

Figure 2 depicts the ITD thresholds, in μs, for each listener as a function of ΔLP, or the increase in bandwidth of the noise in the right ear (for the data in the left panel of Fig. 2, the upper cutoff in the left ear was 125 Hz, and in the right panel it was 250 Hz). ITD thresholds for the 125-Hz upper cutoff condition were higher than for the 250-Hz upper cutoff condition, as is consistent with increased ITD thresholds measured in several studies as the frequency of the sound decreases below 500 Hz (Fitzpatrick and Kuwada, 2001; Yost and Dye, 1988). It is clear from the figures that, for both the 125- and 250-Hz data, increasing the bandwidth of the signal to the right ear

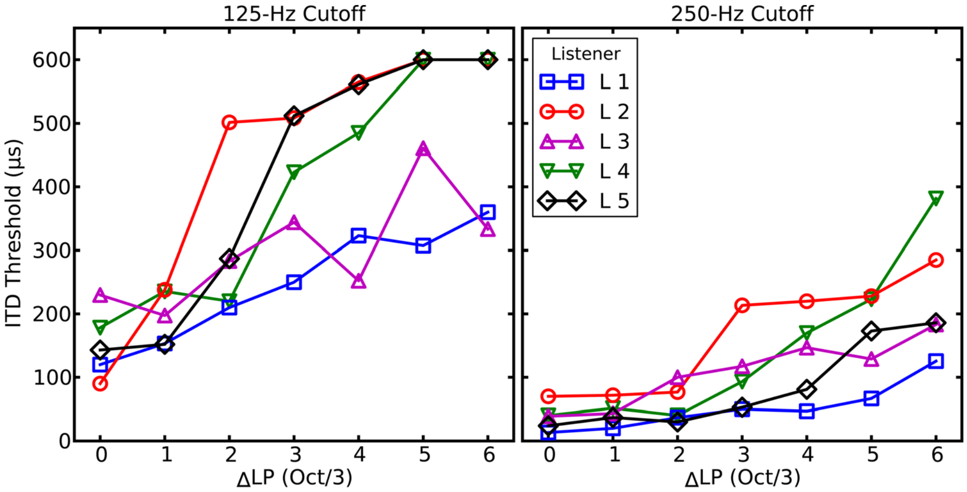

Fig. 2. (Color online) ITD thresholds, in μs, for the five listeners as a function of the difference in low-pass cutoff frequency (ΔLP) between the two ears, which is expressed in 1/3 octaves. The left panel depicts data when the base low-pass cutoff frequency was 125 Hz, the right panel shows 250-Hz data (see Table 1).

(and thus the extent of the monotic high-frequency band) increased ITD thresholds. That is, even though the width of the ISO region was fixed, ITD sensitivity declined with increases in the width of the high-frequency monotic band.

4. Discussion

A two-factor repeated-measures analysis of variance was conducted using left-ear cutoff frequency (125 or 250 Hz) and ΔLP (0–2 octaves) as the independent variables.[1] The analysis revealed statistical significance for both the left-ear cutoff frequency ($p = 0.0006$), and for ΔLP ($p < 0.00001$). The individual data are presented in Fig. 2, and indicate that even when the width of the ISO region is fixed, increasing the bandwidth of the noise in the right ear beyond that present in the left ear leads to increased ITD thresholds. Such increases are much smaller for the conditions in which the ISO region was between 50 and 250 Hz (Fig. 2, right panel) than they were for the condition in which the ISO region was between 50 and 125 Hz (Fig. 2, left panel). This result was somewhat unexpected. Apparently listeners' ability to process ITD changes in a particular frequency region can be influenced by energy in a different region of the spectrum, even when there is a good deal of interaural spectral overlap.

The manipulation in the current study was to increase the bandwidth in one ear while fixing the bandwidth in the other ear. One consequence of this manipulation is that the difference in overall level between the two ears changed with changes in bandwidth. However, it is unclear whether the perception of ILDs is driven by differences in overall level across the two ears (as in the current study), or by interaural differences in spectrum level. We are not aware of any published studies that have examined this issue. However, interaural spectrum-level differences remained constant in the current study, and only differences in total power varied across the ears. It is possible that overall level differences across the two ears played a role in the results by lateralizing the overall image to the right (the side with the monotic flanker and thus the greater power), and it is well-known that binaural sensitivity is reduced as lateralization increases. This possibility does not seem likely, however. If the decreases in ITD sensitivity observed with changes in bandwidth to one ear were caused by the overall ILD change, then we would expect similar patterns of results for the 125- and 250-Hz data, since a particular ΔLP, expressed in octaves, should create the same ILD regardless of the base low-pass cutoff frequency (125 or 250 Hz). For example, a one-octave

ΔLP would produce an overall ILD of 6 dB regardless of the base low-pass cutoff frequency. Thus, ITD sensitivity by a particular listener at a particular ΔLP should be about the same at 125- and 250-Hz. But this is not what we observed.

The stimulus conditions and the results described in the present paper are similar in some respects to studies of binaural interference (see Heller and Richards, 2010, for a recent review). In most binaural interference tasks involving ITDs, ITD thresholds are measured in a narrow band of noise (or with a tone) in one frequency region (target band) while another narrow-band noise (or tone) is presented diotically or dichotically in a different frequency region (the interfering band) remote from the target band. The typical result is that the presence of the interfering band increases the ITD threshold of the target band, usually when the target band is higher in frequency than the interfering band. In the current study, if the region of non-spectral overlap is considered the interferer and the ISO area the target, then the results from this paper are qualitatively similar to the binaural interference results reported previously in the literature. However, the conditions in this study differ from the past work done on binaural interference in several ways. First, the "interferer" is monotic rather than diotic or dichotic. Second, the interferer is spectrally contiguous with the target rather than spectrally separated. Finally, as mentioned previously, the overall level at the right ear increases as bandwidth increases while the overall level at the left ear remains constant. In most studies of binaural interference the ILD averaged across the target and interferer remains about the same. Thus, the present work may indicate an expanded set of conditions in which binaural interference exists.

Heller and Richards (2010) reviewed models (see Buell and Hafter, 1991, and Heller and Trahiotis, 1995) of binaural interference which assume broadband processing of a weighted combination of the interaural differences of the target and interferer. For instance, in these models the ITD of the interferer 'dilutes' the contribution to the weighted sum provided by the ITD of the target, forcing the target ITD to increase for threshold discrimination. In the present study, the difference between the 125-Hz and the 250-Hz low-pass conditions in the increase in ITD threshold with increasing ΔLP (see Fig. 2) depends on the listener. But overall the increase is less for the 250-Hz than for the 125-Hz low-pass condition (note the ITD threshold differences between the two low-pass filter conditions at $\Delta\text{LP} = 0$ Hz). Thus, in terms of the weighted combination models there is a difference in the amount of the target ITD "dilution" that occurs in the two low-pass filter conditions. The weighted combination models would predict the same amount of binaural interference for the two low-pass filter (125 and 250 Hz) conditions.

In the present study the spectral area of non-overlap (ΔLP) could be considered the interfering stimulus, and when it is combined with the target (ISO) area, its monaural presence dilutes the ITD target cue. This "dilution" increases with increasing bandwidth of the spectral area of non-overlap. Another way to view the stimulus conditions of this paper is that the overall interaural level difference dilutes the ITD threshold in the target (ISO) band. In this way, these data are qualitatively consistent with the weighted combination models, i.e., an increase in either the bandwidth of a monaural signal or an increase in overall ILD dilutes the contribution of the target ITD for threshold discrimination. However, it is not possible to derive quantitative predictions using the current models for at least two reasons: (1) the models require an estimate of the interaural threshold for the interferer, which is not possible if the interferer is viewed as the monaural stimulus at the right ear and (2) the interferer is an ILD which would dilute the target ITD. As Heller and Richards (2010) pointed out, when ITD and ILD cues are to be combined within the models one needs a way to equate an ITD cue to an ILD cue, which cannot be done in this case. In addition, the current models do not suggest a way to determine which type of dilution, monaural stimulus or overall ILD, is best for describing the increase in ITD thresholds with increasing ΔLP.

Another way to view the results of the present study is in terms of attention. This view is supported by both informal listening and by reports from the listeners, which suggest that the monotic stimulus at the right ear makes it difficult to attend to the relatively small changes in ITD that occur in a lateral location near the center of the head (i.e., the target ITD). The dominance of the perception of a sound at the right ear increases as the bandwidth of the noise at the right ear increases, accounting for the increased ITD thresholds. As often occurs in cases in which attention may play in role in performance, there are individual differences in this study. Specifically, one listener (the co-author, C.A.B.) appeared to be able to attend to the ISO region in most conditions

We have not been able to determine a quantitative model of this form of attention. The study by Heller and Richards (2010) which used interferers with randomly varying ITDs and ILDs also seems consistent with an attention explanation. They report that more interference was present when the interferers had randomly varying interaural differences compared to when the interferers were diotic. It is possible that the randomly varying interaural differences for interferers (and hence randomly changing positions of the interferers' lateral image) would distract attention away from the target interaural difference.

It seems reasonable to think that binaural interference and attention are related. That is, binaural interference may be the result of a listener's inability to attend to a target or target region in the presence of an interferer.

The results of the present study show that the threshold for detecting an ITD difference in a narrow band of low-frequency noise increases as the bandwidth of the noise on the high-frequency side at one ear increases. The increase in ITD thresholds could be due to a form of cross-frequency integration of a weighted combination of the ITD difference of the target low-pass noise and an overall ILD difference that increases with increasing bandwidth, or to the presence of a highly lateralized monaural stimulus detracting attention from processing a small ITD difference of a centered lateralized image.

Francart and Wouters (2007) conducted a similar experiment, measuring ILD discrimination for 1/3-octave bands of noise, where the band in one ear was shifted up in frequency relative to that in the other ear. Their results indicate an increase in ILD thresholds with increasing spectral separation of the band of noise at one ear relative to that at the other ear for the center frequencies they tested (250–4000 Hz). There was little difference in the ILD threshold shifts with increasing noise band spectral separation as a function of the CF of the noise bands. Thus, it appears as if both ILD and ITD thresholds increase with increasing separation of spectral information in the two ears. Francart and Wouters (2007) did not consider the possible role of attention in their experiments, but their stimulus conditions are similar to the ones used in the present experiment, which suggests that attention may have played a role in the increase ILD thresholds they obtained.

This study was partially motivated by the idea that cochlear implant patients with residual hearing in both ears might be able to process ITD differences even when the spectral regions of residual hearing are not the same at the two ears (a similar motivation was discussed in Francart and Wouters, 2007). These studies suggest that as long as there is an ISO region, CI patients with bilateral residual hearing might be able to process interaural differences so long as the frequency extent of residual hearing at each ear does not vary by very much. This assertion does not take learning into account, however. The bandwidths of both the "target" (ISO) and "interferer" frequency regions in the current study were acoustically novel for the listeners, changed from run to run, and their exposure was acute. There was little time for a listener to adapt to a given configuration, as conditions were varied randomly within a testing session. Given that in the current study, the listener with the most experience showed the lowest thresholds, learning may play a role in overcoming an asymmetrical low-frequency configuration. Because the bilateral low-frequency audiometric configuration of a particular CI listener is more or less static, it may be that we are overestimating the deleterious effects of interaural spectral asymmetry for these patients.

Acknowledgments

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[1] The authors believe that in conditions like those used in the current experiment, it is more statistically sound to report individual data than to report inferential statistics based on mean data, particularly when the data from every subject show the reported trends. Since a Reviewer and the Associate Editor required that inferential statistics be reported, we have done so.

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