Published in final edited form as:
Ear Hear. 2008 October ; 29(5): 674–683. doi:10.1097/AUD.0b013e3181775e03.

Interaural time discrimination of envelopes carried on high-frequency tones as a function of level and interaural carrier mismatch

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Abstract

Objectives—The present study investigated interaural time discrimination for binaurally mismatched carrier frequencies in listeners with normal hearing. One goal of the investigation was to gain insights into binaural hearing in patients with bilateral cochlear implants, where the coding of interaural time differences may be limited by mismatches in the neural populations receiving stimulation on each side.

Design—Temporal envelopes were manipulated to present low frequency timing cues to high frequency auditory channels. Carrier frequencies near 4 kHz were amplitude modulated at 128 Hz via multiplication with a half-wave rectified sinusoid, and that modulation was either in-phase across ears or delayed to one ear. Detection thresholds for non-zero interaural time differences were measured for a range of stimulus levels and a range of carrier frequency mismatches. Data were also collected under conditions designed to limit cues based on stimulus spectral spread, including masking and truncation of sidebands associated with modulation.

Results—Listeners with normal hearing can detect interaural time differences in the face of substantial mismatches in carrier frequency across ears.

Conclusions—The processing of interaural time differences in listeners with normal hearing is likely based on spread of excitation into binaurally matched auditory channels. Sensitivity to interaural time differences in listeners with cochlear implants may depend upon spread of current that results in the stimulation of neural populations that share common tonotopic space bilaterally.

suggested keywords

binaural hearing; cochlear implant; localization; ITD

I. Introduction

Under natural listening conditions, listeners with normal hearing use differences in the sound streams reaching each ear to get a sense of the three-dimensional auditory scene. This process underlies the ability to localize sound sources and facilitates processing of a masked signal when the signal and masker sources are separated in space. Binaural cues are often differentiated into interaural level difference (ILD) and interaural time difference (ITD) cues. For spectrally simple stimuli, ILD cues dominate localization at high frequencies and ITD cues dominate localization at low frequencies, a relationship that is often referred to as Rayleigh's duplex theory of localization. It has also been demonstrated that listeners are sensitive to ITDs

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associated with the envelopes of high-frequency carriers (Henning, 1974; McFadden & Pasanen, 1976). While these cues combine with other cues for auditory localization under natural listening conditions (e.g., spectral cues to elevation), the ITD cues are thought to dominate localization of complex stimuli containing low frequencies (e.g., Wightman & Kistler, 1992). The ability to localize sound sources is useful in its own right, but it also facilitates understanding of speech-in-noise when the speech and noise sources are located at different points on the azimuthal plane (e.g., Plomp & Mimpen, 1981).

It is well accepted that some listeners with hearing impairment demonstrate a binaural advantage when listening through appropriately fitted binaural hearing aids (e.g., Byrne, 1981). There is a growing body of evidence that bilateral cochlear implantation also improves localization relative to unilateral implantation (Grantham, Ashmead, Ricketts, Labadie, & Haynes, 2007; Lawson, Wolford, Brill, Schatzer, & Wilson, 2001; Nopp, Schleich, & D'Haese, 2004; van Hoesel, Ramsden, & Odriscoll, 2002; van Hoesel & Tyler, 2003). Psychophysical studies suggest that patients with bilateral implants are able to make use of ILDs with a high degree of accuracy. There is considerable evidence that their ability to make use of ITDs is often poor in comparison to performance obtained by listeners with normal hearing (Grantham et al., 2008; Laback, Pok, Baumgartner, Deutsch, & Schmid, 2004; Long, Carlyon, Litovsky, & Downs, 2006; van Hoesel & Clark, 1997). However, better-functioning listeners with cochlear implants can detect ITDs in the range of 55–200 μs under some conditions (van Hoesel, 2007), such as low-rate pulse trains (e.g., 100 pulses per second) or pulse trains receiving low-rate amplitude modulation. Van Hoesel (2004) has also noted that listeners with bilateral implants may benefit from interaural time cues under conditions where ILD cues are ambiguous and the rate of stimulation is relatively low. It has been suggested that the impaired ITD discrimination found in many cases with bilateral cochlear implants may be due, at least in part, to a mismatch in neural populations receiving stimulation across ears (Long et al., 2006; van Hoesel & Clark, 1997). A similar argument has been made in the domain of hearing aid research; diplacusis, a mismatch in perceived pitch across ears, has been suggested to play a role in the failure to make optimal use of binaural cues in some listeners with hearing aids (Markides, 1977).

The mismatch in stimulation across ears in patients with bilateral cochlear implants could be due to differences in electrode placement, neural survival, and/or anatomical differences affecting spread of current in the cochlea. Binaural pitch matching has been used as a tool to identify pairs of electrodes *closely* (if not perfectly) matched in terms of the responsive neural populations, and hence the most likely to support good binaural processing. This procedure has been used in several laboratory studies with promising results (Lawson, Wilson, Zerbi, van den Honert, Finley et al., 1998; Lawson et al., 2001; van Hoesel & Clark, 1997). Both ITD and ILD tend to be optimal for pitch-matched electrodes (e.g., Laback et al., 2004), but there are exceptions (Long, Eddington, Colburn, & Rabinowitz, 2003). While some studies have demonstrated that ITD discrimination on the order of 50–150 μs is possible in electric hearing when pitch-matched electrodes are used to deliver the stimulus, there is also evidence that place mismatches may not be as critical as expected based on Greenwood's map of the place-to-frequency relationship in the cochlea (Greenwood, 1961). For example, a study by van Hoesel and Clark (1997) showed that fairly large offsets are necessary to interfere with ITD discrimination performance (e.g., 4–8 electrodes, or 3–6 mm). While the listeners in that study showed relatively poor ITDs even for matched electrodes, this result suggests that mismatches in the place of stimulation at the two ears may not be particularly detrimental. Such findings have led to speculation about the role of current spread in binaural hearing, with slight mismatches in electrode placements bilaterally being offset by the wide population of auditory fibers responding to stimulation at each electrode (van Hoesel, 2004).

Relatively little attention has been paid to the importance of frequency matches across ears for the processing of ITD information in listeners with normal hearing, in part because the binaural match in neural populations responding to a given stimulus frequency is assumed to be quite close. While there is some evidence for subtle mismatches in place of transduction across ears in listeners with normal hearing, both with changes in stimulus level and with normal variation in physiology (Burns, 1982), few data are available on the possible implications for binaural hearing. Likewise, there is little information about whether the auditory system is adept at accommodating to binaural mismatches in frequency that might be associated with hearing loss. Existing data do suggest some plasticity in the binaural processing of adult listeners that occurs either in response to experimentally induced and reversible binaural asymmetries (Florentine, 1976; Moore, Hine, Jiang, Matsuda, Parsons et al., 1999), conductive hearing loss (Hall, Grose, & Pillsbury, 1995), or slight asymmetries that occur in listeners with clinically normal hearing (Simon, Collins, Jampolsky, Morledge, & Yu, 1994). Furthermore, several days of exposure to experimentally induced unilateral time delays can shift perceived lateralization in adults with normal hearing, an effect which decays quickly to pre-exposure baseline after removal of the delays (Javer & Schwarz, 1995). It is unclear whether significant binaural place and/or pitch mismatches could likewise be accommodated, or whether the comparison across ears is necessarily restricted to matched frequency channels.

Mechanics of cochlear transduction make it impossible to experimentally introduce a substantial place shift in an otherwise binaurally matched stimulus at low frequencies in listeners with normal hearing. Specifically, it is not possible to independently manipulate place of stimulation and temporal fine structure across ears. Amplitude modulated high-frequency tones can be manipulated in this way, however, to permit distinction between place of stimulation and ITD information as carried by the envelope (e.g., Henning, 1974). Basing the envelope on a half-wave rectified, low-frequency waveform (van de Par & Kohlrausch, 1997), sometimes referred to as ‘transposed’ AM, has produced binaural hearing results comparable to those observed at low frequencies (Bernstein & Trahiotis, 2002; 2003), provided that the rate of modulation is relatively low (e.g., below 300 Hz). Offsetting the carrier frequencies of high-frequency AM stimuli can introduce binaural mismatches in otherwise binaurally matched stimuli, provided that the carrier is above the limit where fine-structure contributes to binaural hearing, estimated to be between 1 and 2 kHz in humans (for a review, see van de Par & Kohlrausch, 1997).

This general approach has been used in several psychophysical studies on listeners with normal hearing. Henning (1974) showed that lateralization for sinusoidally amplitude modulated high frequency tones worsens when the carrier frequencies are mismatched across ears, and Nuetzel and Hafter (1981) emonstrated an analogous effect for ITD detection. Poon, Hwang, Yu, Chan, and Kwok (1984) examined ITD sensitivity as a function of binaural stimulus frequency mismatches using tone pips and click stimuli, and observed that the spectral width of the stimuli correlated with ability to judge lateralization. They interpreted this result as indicating that binaural spectral overlap of stimulation is important for lateralization. In a related paradigm, McFadden and Pasanen (1975) collected data on the binaural beat based on the envelopes of high-frequency stimuli and reported that beats can be heard for carrier frequencies that are well separated across ears (e.g., 2 kHz in one ear and 3 kHz in the other). Recent results from a similar binaural beat paradigm indicated that ITD sensitivity for envelope falls off gradually with the introduction of across-ear carrier mismatches, with some evidence of sensitivity remaining for mismatches of up to 2 octaves (Blanks, Roberts, Buss, & Fitzpatrick, 2007). Rowan and Lutman (2006) showed that training on a matched-carrier binaural envelope ITD task was associated with parallel improvements in performance of ITD discrimination in both matched and mismatched carrier stimuli; this was interpreted as evidence that the same cue or set of cues underlie sensitivity whether the carriers are matched or offset across ears.

Although the above studies clearly indicate ITD sensitivity for interaurally mismatched carrier frequencies, the basis of the effect is unknown. If the ITD cue is based on information from matched frequency regions across ears, then spread of excitation from mismatched carriers could introduce energy into matched binaural channels. Manipulation of stimulus level is associated with changes in spread of excitation, generating the prediction that carrier frequency mismatches should be less disruptive to ITD processing when the stimulation level is relatively high. Although the effects of level on ITD processing with binaurally mismatched stimuli have not been explored, several studies have shown that ITD sensitivity with spectrally matched stimuli improves with increasing stimulus level (e.g., Cohen, Koehnke, McClave, & Pallanck, 1985; Zwislocki & Feldman, 1956), particularly for high-frequency carriers (Simon et al., 1994; Smith-Olinde, Besing, & Koehnke, 2004) where performance is presumably based upon temporal envelope cues.

Another possibility to account for binaural sensitivity in the presence of interaural carrier frequency mismatches is a mechanism that compares interaural envelope timing *across* frequency channels. Although there is currently no physiological evidence for this specific mechanism, there is speculation that certain binaural (Schroeder, 1977; Shamma, Shen, & Gopalaswamy, 1989) and monaural (Loeb, White, & Merzenich, 1983; Shamma & Klein, 2000) processes depend upon the analysis of timing differences across frequency regions.

The experiment described in the current report used amplitude-modulated high-frequency tones to explore the effects of experimentally induced binaural mismatches on ITD discrimination in listeners with normal hearing. It is hypothesized that envelope ITD processing is performed based on information in binaurally matched frequency channels, and that performance of this task with mismatched carrier frequencies is based on spread of excitation into matched channels that are intermediate with respect to the two carriers. This paradigm provides a valuable simulation of binaural cues that may be available to listeners with bilateral cochlear implants, and has several advantages over testing listeners with implants directly. In contrast to listeners with implants, the normal population is characterized by much more consistent neural responsivity across cochlear place and more consistent history of good binaural stimulation. Furthermore, varying cochlear mismatch by way of carrier tone frequency allows arbitrary mismatches to be introduced (as well as a normal binaural match), while electrical stimulation is restricted by the number and placement of active electrodes available in each cochlea. Limitations of this simulation should also be kept in mind, however. Whereas the present paradigm provides an opportunity to observe the effects of bilateral frequency mismatches on ITD discrimination, the associated acoustical stimulation necessarily results in patterns of neural activity that differ in detail from those occurring with electrical stimulation (Middlebrooks, Bierer, & Snyder, 2005). A further consideration is that listeners with bilateral cochlear implants have a greater opportunity to adapt to binaural mismatches than do listeners with normal hearing who experience binaural mismatches only in the context of the experiment.

In summary, the purpose of the experiment was to parametrically explore the effects of carrier frequency mismatches across ears on ITD discrimination and to assess the role of across frequency channel effects, if any. Whereas existing data suggest that sensitivity will fall off with increasing carrier frequency mismatch, the effects of stimulus level on this effect have not been systematically described. If spread of excitation into binaurally matched frequency channels underlies binaural performance irrespective of carrier frequency mismatches, then performance should be sensitive to changes in level, particularly in cases of large frequency asymmetry. Envelope ITD discrimination for a stimulus with reduced spectral spread was also measured to evaluate the role of the spectral width of the stimulus. Masking noise was introduced in a subset of conditions in order to manipulate the availability of frequency regions providing information. A low-pass masker was introduced to assess whether low-frequency distortion tones contributed to performance in the unmasked case. A bandpass masker intermediate with respect to the two mismatched carrier frequencies was used to evaluate the role of spread of excitation into the intermediate frequency region.

II. Methods

A. Listeners

Listeners were the first three authors, ages 28 to 49. All had pure-tone thresholds of 20 dB HL or better bilaterally at octave frequencies 250–8000 Hz (American National Standards Institute, 1996), and no history of ear disease.

B. Stimuli

Stimuli were high-frequency carrier tones, amplitude modulated via multiplication with a rectified, 128-Hz sinusoid. This rate was chosen based on the data of Bernstein and Trahiotis (2002), who showed that at 128 Hz the envelope ITD threshold for a “transposed” stimulus at 4 kHz was similar to the ITD of a 128-Hz pure tone. In matched-carrier conditions the carrier tones were identical 4000-Hz sinusoids. The left column of Figure 1 shows the time and frequency domain characteristics of this stimulus (top and bottom panels, respectively). In cases of mismatch, the two tones were arithmetically centered on 4000 Hz with frequencies of 4000 ± 200, 400, 800 or 1600 Hz. The level of the stimulus was defined as the level of a tone with equivalent peak amplitude (pSPL), a value that is 6 dB greater than the overall stimulus level over a long duration sample. For the matched-carrier conditions, data were taken at a range of levels spanning 20 to 70 dB pSPL, in 10-dB increments. For the mismatched-carrier conditions, data collection was performed at 30, 50 and 70 dB pSPL. Thresholds were also collected in a subset of conditions where all but four of the spectral sidebands associated with half-wave rectified AM were omitted. This was achieved by lowpass filtering the modulator stimulus at 300 Hz prior to multiplication with the carrier. The resulting ‘restricted-spectrum’ stimulus has a 512-Hz bandwidth. This stimulus has been shown to support good binaural ITD processing (Bernstein & Trahiotis, 2002), but it also produces a more focused excitation and as such provides a more stringent test of the ability to utilize binaural ITD information in the face of carrier frequency mismatches. The right column of Figure 1 shows examples of the time and frequency domain characteristics of this stimulus.

Data were collected in the presence of masking noise for a subset of conditions. These maskers were generated in the frequency domain by zeroing out components not falling in the masker pass-band. These samples were based on 2^{17} points, which when played out at 24,414 Hz produced a waveform segment of approximately 5.4 seconds that could be played continuously without any discontinuities. In one manipulation a low-pass noise was used to assess whether low-frequency distortion products contribute to ITD sensitivity; the low-pass masker was intended to interfere with the use of any low frequency information associated with phase locking. This masker had a low-pass cutoff of 1300 Hz and was played diotically at 20 dB/Hz (for a total of ~51 dB SPL). In another manipulation a bandpass masker interposed between two mismatched carriers (4000 ± 800) was used to assess the role of spread of excitation into a binaurally matched frequency channel using restricted-spectrum stimuli at 70 dB pSPL. The bandpass masker was a diotic Gaussian noise played continuously at 60 dB SPL and filtered to a bandwidth of 100 Hz arithmetically centered on 4000 Hz. This level was chosen based on estimated excitation patterns (Glasberg & Moore, 1990) for stimuli presented at 70 dB pSPL and centered on either 3200 or 4800 Hz; in each case the predicted peak excitation at 4000 Hz is just under 60 dB SPL.

In all conditions the starting envelope phase was random on each presentation interval. Envelope ITD was manipulated by adjusting the relative starting phases of the 128-Hz tones used to modulate the left and right ear carrier. The carrier tone phase was not affected by this manipulation, and the carrier ITD was always zero. Stimuli were 500-ms in duration, ramped on and off with 40-ms $\cos^2$ ramps. Stimuli were generated in software (MATLAB controlling RPVDs; TDT), played out at 24,414 Hz (RP2; TDT), routed through a headphone buffer (HB7; TDT), and presented by way of deeply inserted earphones (ER2; Etymotic).

C. Procedures

Listeners performed a two-cue, two-alternative forced choice task. There were four listening intervals, and the signal occurred in either the 2^{nd} or 3^{rd} interval, selected at random. In the signal interval the envelope was delayed to one ear, with the direction of the ITD (left leading vs. right leading) randomly selected on every trial. In the standard intervals the envelope was identical across ears. Feedback was given visually after every trial. The ITD was adjusted using a 3-down, 1-up stepping rule to estimate 79% correct (Levitt, 1971). At the beginning of the track ITD adjustments were made in factors of 1.41 in units of time (μs). This step size was reduced to 1.19 after the second track reversal. A track continued until 8 track reversals were obtained, and the final threshold estimate was computed as the geometric mean of the ITD at the last 6 track reversals. Thresholds greater than 1000 μs were judged to be unmeasureable based on literature suggesting that increases in lateralization fall off rapidly beyond this point (Bernstein & Trahiotis, 2003; Mossop & Culling, 1998).

All thresholds were obtained in blocks by condition, with 4 or 5 estimates obtained sequentially, and the geometric mean is reported below. The matched-carrier conditions were tested first, with listeners completing conditions at the highest presentation level first and proceeding down in level. The mismatched carrier conditions were then completed. In these conditions listeners began with small mismatches and progressed out to larger separations until threshold approached ceiling (1000 μs). At each separation, listeners first heard stimuli with the higher-frequency carrier presented to the right ear, and after completing a block of these stimuli went on to the complementary (left-high) condition. This order was reversed in later test sessions.

Because this task is highly sensitive to training effects, care was taken to train each listener in the matched-carrier conditions until performance was stable, with practice spanning 20 hours or more in some cases. Listening was performed over a relatively short period of time (1–2 months), in part to ensure maintenance of training effects. Observers 1 and 2 completed the entire experiment twice to ensure stability of the data and to guarantee there was no change in thresholds if the stimuli were presented in a different order. There was no systematic evidence of improvement on retest, so data from the initial testing blocks were retained for all three observers. The protocol for this experiment was approved by the Institutional Review Board of the University of North Carolina, School of Medicine.

III. Results

Figure 2 shows threshold ITD at matched carrier frequencies as a function of stimulus level, with symbols indicating stimulus condition. Missing data for the 20-dB pSPL level for Observers 1 and 3 indicate that threshold exceeded the upper limit of 1000 μs. In the baseline condition, consisting of the unfiltered half-wave rectified AM with no low-pass masking, thresholds decreased with increasing the level (open circles). The lowest ITD threshold for all listeners was at 70 dB pSPL, and performance at this level ranged from 28–51 μs. Effects of including the lowpass masker (black-filled circles) appear to be level dependent. Thresholds for the masked and unmasked conditions are similar at the lowest two levels, but the masked thresholds are elevated with respect to the highest level by a factor of 1.3 to 3.8 relative to the unmasked condition at the highest level. This result suggests that low-frequency distortion products and/or spread of excitation into low frequency regions may have contributed to thresholds at 70 dB pSPL, particularly for Observers 1 and 3, but probably did not at 50 and 30 dB pSPL presentation levels. The combined effects of restricting the spectral sidebands and including the lowpass masker differ across listeners (grey-filled circles). For Observer 1, restricting sidebands elevates thresholds by a factor of 1.6 to 1.9 across levels relative to the masked half-wave rectified condition. The effect is slightly larger for Observer 3, with thresholds elevated by a factor of 1.9 to 2.5 across frequency. For Observer 2 the restricted-spectrum manipulation appears to be level dependent, elevating thresholds by a factor of 1.6–1.9 at the lower levels and by a factor of 3.2 at the 70-dB stimulus level. This result suggests that the restricted-spectrum stimulus may be inferior to the half-wave rectified AM stimulus at conveying ITD information under some conditions.

Figure 3 shows the results of the mismatch-carrier conditions collected with the half-wave rectified AM stimulus in the absence of a masker. ITD thresholds are plotted as a function of carrier tone frequency mismatch, with individual listeners' data plotted in separate panels. Data for the 0-Hz mismatch are re-plotted from Figure 2. Symbols indicate both the stimulus level and the ear receiving the higher of the two mismatched carrier tones, as defined in the legend. As in the matched-carrier conditions the best performance, or lowest ITD threshold, is obtained with the highest stimulus level. Sensitivity declined with increases in carrier frequency mismatch.

Results with the restricted-spectrum stimulus in the presence of a lowpass masker produced a similar pattern of results to that shown in Figure 3, with a trend towards reduced sensitivity. These data are shown for the 70-dB pSPL level in Figure 4, with data from Figure 3 replotted for comparison. The effect of removing stimulus sidebands and including a lowpass masker was variable across observers; Observers 1 and 3 showed little or no effect on thresholds in the mismatched carrier conditions, while thresholds of Observer 2 were consistently elevated by a factor of approximately 2.3. The increase in ITD at 0 μs, for all observers, maybe due to the disruption of diotic distortion tones present at 70 dB. Thresholds taken in the presence of a bandpass masker intermediate with respect to the carrier tones at 4000 ± 800 are not shown in this figure because they were greater than 1000 μs in all cases.

One surprising aspect of the data shown in Figure 3 is the trend for better performance when the high frequency carrier was presented to the right ear. This trend is most evident in the results of Observer 3 for the 50-dB stimulus level, where thresholds differed by a factor of approximately 2.3 based solely on which ear was presented with the higher-frequency carrier tone. The significance of the ear effect was assessed with a repeated measures ANOVA, including all data taken for the 200- and 400-Hz separation, with further separations omitted due to ceiling performance for the lowest level of presentation. There was a significant main effect of the ear of presentation ($F_{1,2}=21.1$, $p<0.05$) and no significant interaction with stimulus level or degree of carrier mismatch. Several possible explanations for the effect were examined. Initially it was hypothesized that test-order effects could have contributed to better performance in the right-high conditions, as these conditions were frequently tested before the complementary (left-high) conditions. For example, the finding might have been related to fatigue or to some kind of training/listening-strategy effect whereby exposure to right-high conditions negatively affected sensitivity in a subsequent left-high condition. Extensive additional practice failed to reverse this trend, however, suggesting that order/exposure effects were probably not of consequence. All equipment was thoroughly tested to ensure that this result was based on observer ear differences rather that hardware channel differences. Perhaps the most compelling evidence in this regard is that reversing the insert earphone configuration – inserting the 'left' phone in the right ear and visa versa – did not impact the ear bias, indicating that asymmetry cannot be traced back to the sound presentation system.

IV. Discussion

This experiment replicated the previous results showing that envelope-based ITD sensitivity decreases with the introduction of carrier frequency mismatches (e.g., Henning, 1974). These data reflect sensitivity to envelope ITD, as contrasted with fine-structure ITD, since the fidelity of temporal fine structure information falls off precipitously between 1 and 2 kHz (e.g., Zwislocki & Feldman, 1956). There were marked individual differences in these data, despite the fact that all three observers were highly practiced in psychophysical tasks. Analogous individual differences and practice effects have been previously noted for this task (Rowan & Lutman, 2006). Despite the individual differences, the general pattern of data was consistent across observers.

For matched-carrier stimuli, threshold ITD varied as a function of stimulus level. Thresholds were on the order of 40 μs at 70 dB pSPL, and at 30 dB pSPL thresholds were on the order of 400 μs. The decrease in ITD thresholds found with an increase in intensity may be due to spread of excitation and an associated increase in the number of matched auditory channels providing binaural cues. This result is consistent with previous reports that sensitivity to binaural ITD cues based on envelopes of high-frequency stimuli improves substantially with increasing stimulus level (e.g., Simon et al., 1994; Smith-Olinde et al., 2004). Better performance of an ILD task with increased level was recently argued to be due to spread of signal excitation, increasing the number of auditory channels from which to derive a binaural difference cue (Stellmack, Viemeister, & Byrne, 2004); a similar effect based on spread of excitation could be responsible for the ITD results.

Data collected with a lowpass masker suggest that low-frequency distortions could have contributed to sensitivity at the highest levels tested, but that performance was probably based primarily, or solely, on information in high-frequency regions (>1300 Hz) for levels of 30 and 50 dB pSPL. Further, these data show that the presence of a masker distant from the signal frequency itself does not necessarily elevate thresholds. This is consistent with previous data showing that the across-channel masking effects observed at low carrier frequencies, referred to as binaural interference, are small or absent for transposed AM stimuli (Bernstein & Trahiotis, 2004, 2005).

For mismatched carrier conditions, thresholds rose with increasing frequency mismatch. There was also an effect of level, in that ITD sensitivity extended out to larger carrier mismatches for high than for low stimulus level. In the present data this effect appeared to depend on the ear receiving the higher frequency, with better performance when the right ear received the higher frequency tone, though this result was quite variable across observers and conditions. A level effect in the tolerance to carrier frequency mismatch is consistent with the idea that the cue underlying performance is based on the spread of excitation from each of the carriers into a binaurally matched channel or set of channels, with matched channels excited over a wider frequency separation at higher stimulus presentation levels. Reduction of stimulus bandwidth and inclusion of a lowpass masker tends to elevate threshold for the highest stimulus level, though the magnitude of this effect is variable across observers. Introducing a masker intermediate with respect to the two mismatched carriers increases thresholds above the 1000 μs ceiling. This result is consistent with the idea that spread of excitation into matched frequency channels forms the basis of the cue supporting envelope ITD processing for mismatched carrier frequencies, though some contribution of binaural interference (Bernstein & Trahiotis, 2005) cannot be ruled out.

While the discussion up to this point has assumed that ITD detection thresholds represent sensitivity of binaural processing similar to that underlying localization, the task could also theoretically be performed based on envelope coherence cues unrelated to localization, such as across-channel envelope difference cues (e.g., Strickland, Viemeister, Fantini, & Garrison, 1989). This seems unlikely based on the observers' subjective impression that detection was based on lateralization, but additional data were collected to corroborate that impression. In this supplemental task observers listened to restricted-spectrum stimuli at 4000 ± 800 Hz, presented at 70 dB pSPL and in the presence of the lowpass masker. For a suprathreshold ITD of 1000 μs all observers were at or near 100% correct at identifying whether the stimulus was delayed to the right or left ear (i.e., lateralized to the left or to the right). Impressions of lateralization and fusion, as well as accuracy in lateralization, decreased for ITDs greater than 1000 μs (the threshold ceiling). This is consistent with the interpretation that ITD detection thresholds represent binaural processes related to localization and corroborates the choice of 1000 μs as a ceiling ITD in the current paradigm.

The present results indicated that high stimulus levels are associated with a relatively high level of ITD sensitivity for both matched and mismatched carrier frequency conditions. It is possible that the spread of excitation associated with high-level stimulation may underlie this effect for both the matched and mismatched carrier conditions. Such spread of excitation may increase the number of frequency-matched auditory channels upon which to base ITD processing. Combination of cues across pairs of frequency-matched auditory channels has been suggested to improve performance in other binaural tasks using spectrally narrow stimuli, including the binaural masking level difference (Breebaart, van de Par, & Kohlrausch, 2001; van de Par & Kohlrausch, 1999) and interaural level discrimination (Stellmack et al., 2004).

One goal of the present experiment was to simulate in observers with normal-hearing the envelope ITD cues available to patients with cochlear implants. A recent study by van Hoesel et al. (2007) measured envelope ITD thresholds for a 100-Hz sinusoidal modulation carrier on a 6 kHz pulse train. Stimuli were presented on matched electrodes, as identified by x-ray and subjective pitch comparisons, and played at 80% of the subjective dynamic range. Observers were screened for good ITD sensitivity for low-rate pulse trains, so their results are likely more representative of best performance than average performance. Thresholds in the van Housel study ranged from approximately 50 to 200 μs. These results compare favorably to the 100-μs thresholds obtained in the present study with the 70-dB pSPL stimulus in the presence of a lowpass masker, a condition with significant spread of excitation but reduced opportunity for use of cues falling below 1300 Hz. Other studies have reported significantly poorer performance on envelope ITD tasks (e.g., van Hoesel et al., 2002). Based on data from Figure 4, frequency separations associated with thresholds of 400–800 μs for the 70 dB pSPL stimulus level are on the order of 800 Hz or more in the current study. When centered on 4-kHz, this frequency span corresponds to a 2.7 mm separation (Greenwood, 1961; Liberman, 1982), a value within the range of binaural implant mismatches reported when assessed via pitch matching (van Hoesel & Clark, 1997).

These results suggest that bilateral mismatches in listeners with cochlear implants, as simulated here in listeners with normal-hearing, could play a significant role in reduced envelope ITD performance. However, bilateral mismatches alone probably cannot account for the wide range of sensitivity observed in listeners with cochlear implants. For example, in the patient tested by van Hoesel et al. (2002), sensitivity to ITD was stable until the offset in place of stimulation between the two sides was more than 4–8 electrodes, corresponding to 3–6 mm. This is analogous to +/−900 to +/−1700 Hz around 4 kHz in the current paradigm, by which point large and progressive degradations in performance were already apparent. Van Hoesel (2002) interpreted this resistance to the disruptive effects of electrode separation as reflecting substantial spread of current that could offset the mismatches in place of stimulation across ears. The results of a listener with bilateral cochlear implants tested by van Hoesel (2004) were also consistent with spread of current as an important factor; this listener obtained relatively a good ITD threshold (approximately 100 μs) in one condition where electrodes were bilaterally pitch matched, and showed relatively small reductions in ITD sensitivity for electrode pairings that were one-to-two bands offset from a pitch-matched condition. In conjunction with the data from the current study, these results imply that efforts to decrease current spread in listeners who are bilaterally implanted could result in worsening of ITD processing. This is consistent with previous data on the level effects noted for ITD performance in electric hearing (van Hoesel, 2007).

A second goal of this experiment was to gain insight into the mechanism or mechanisms underlying envelope ITD processing for mismatched carrier tones in acoustic hearing. One hypothesis is that this task relies on spread of excitation into one or more binaurally matched auditory channels intermediate between the two carriers. The effects of level, restricting the spectrum of the stimulus, and including bandpass noise between mismatched carrier frequencies were generally consistent with hypothesis. Increased level would be associated with greater spread of excitation, such that within-channel cues would be available at wider carrier separations for higher stimulus levels. Similarly, the presence of widely spaced sidebands would be associated with more opportunities for within-channel cues with the introduction of carrier frequency separation.

Although the present results are generally consistent with a spread of excitation hypothesis, they do not rule out the possibility that across-frequency comparisons can contribute to ITD sensitivity. Furthermore, as noted in the introduction, it is not known whether long-term experience with ITDs carried by binaurally mismatched carriers (as might occur in patients having extended experience with bilateral cochlear implants) might be associated with neural plasticity that could enhance sensitivity to the relevant temporal cues. It is therefore possible that patients with bilateral cochlear implants might exhibit a stronger ability to benefit from binaural temporal cues carried by mismatched frequency channels than suggested by the present data from listeners with normal hearing.

V. Conclusions

The present results support the following conclusions:

1. The ability to detect an envelope ITD for matched 4-kHz carriers can be quite good, and sensitivity improves with increasing stimulus level. ITD thresholds in the presence of a lowpass masker suggest that performance is based on temporal information carried in high frequency channels for the lower stimulus levels of 30- and 50-dB pSPL. Restricting the spectral extent of the stimulus reduces sensitivity somewhat at all levels tested.

2. Introduction of carrier frequency mismatches is associated with incremental degradations in performance. Listeners tolerated greater mismatches at higher stimulus presentation levels, an effect that was also found after restricting stimulus sidebands and introducing a lowpass masker. Masking noise that was bandpass filtered and centered on 4000 Hz prevented observers from performing the task for ITDs below 1000 μs.

3. While the study described here does not rule out the possibility of across-channel cues to ITD, most of the data presented are consistent with the hypothesis that within-channel cues dominate performance of ITD lateralization.

4. The present envelope ITD paradigm may provide insights into ITD processing in listeners with cochlear implants. Results lend further support for the suggestion that stimulus level and spread of current within the cochlea could play an important role in bilateral cochlear implant performance.

Acknowledgements

This work was supported by two grants from NIH NIDCD: RO1 DC000418 and T32 DC005360.

References

American National Standards Institute. American National Standards Specification for Audiometers (ANSI S3-1996). New York: ANSI; 1996.

Bernstein LR, Trahiotis C. Enhancing sensitivity to interaural delays at high frequencies by using “transposed stimuli”. Journal of the Acoustical Society of America 2002;112:1026–1036. [PubMed: 12243151]

Bernstein LR, Trahiotis C. Enhancing interaural-delay-based extents of laterality at high frequencies by using “transposed stimuli”. Journal of the Acoustical Society of America 2003;113:3335–3347. [PubMed: 12822805]

Bernstein LR, Trahiotis C. The apparent immunity of high-frequency “transposed” stimuli to low-frequency binaural interference. Journal of the Acoustical Society of America 2004;116:3062–3069. [PubMed: 15603151]

Bernstein LR, Trahiotis C. Measures of extents of laterality for high-frequency “transposed” stimuli under conditions of binaural interference. Journal of the Acoustical Society of America 2005;118:1626–1635. [PubMed: 16240822]

Blanks DA, Roberts JM, Buss E, Fitzpatrick DC. Neural and behavioral sensitivity to ITDs in the envelopes of amplitude modulated tones with mismatched carrier frequencies. Journal of the Association for Research in Otolaryngology. 2007in press

Breebaart J, van de Par S, Kohlrausch A. Binaural processing model based on contralateral inhibition. II. Dependence on spectral parameters. Journal of the Acoustical Society of America 2001;110:1089–1104. [PubMed: 11519577]

Burns EM. Pure tone pitch anomalities. I. Pitch-intensity effects and diplacusis in normal ears. Journal of the Acoustical Society of America 1982;72:1394–1402. [PubMed: 7175025]

Byrne D. Clinical issues and options in binaural hearing aid fitting. Ear and Hearing 1981;2:187–193. [PubMed: 7297782]

Cohen MF, Koehnke J, McClave AE, Pallanck PG. The comparative effects of signal sensation level and sound-pressure level on interaural time discrimination. Journal of the Acoustical Society of America 1985;78:908–915. [PubMed: 4031261]

Florentine M. Relation between lateralization and loudness in asymmetrical hearing losses. Journal of the American Audiology Society 1976;1:243–251. [PubMed: 931759]

Glasberg BR, Moore BCJ. Derivation of auditory filter shapes from notched-noise data. Hearing Research 1990;47:103–138. [PubMed: 2228789]

Grantham DW, Ashmead DH, Ricketts TA, Haynes DS, Labadie RF. Interaural Time and Level Difference Thresholds for Acoustically Presented Signals in Post-Lingually Deafened Adults Fitted with Bilateral Cochlear Implants Using CIS+ Processing. Ear and Hearing 2008;29:33–44. [PubMed: 18091105]

Grantham DW, Ashmead DH, Ricketts TA, Labadie RF, Haynes DS. Horizontal-plane localization of noise and speech signals by postlingually deafened adults fitted with bilateral cochlear implants. Ear and Hearing 2007;28:524–541. [PubMed: 17609614]

Greenwood DD. Critical bandwidth and the frequency coordinates of the basilar membrane. Journal of the Acoustical Society of America 1961;33:1344–1356.

Hall JW, Grose JH, Pillsbury HC. Long-term effects of chronic otitis media on binaural hearing in children. Archives of Otolaryngology Head & Neck Surgery 1995;121:847–852. [PubMed: 7619408]

Henning GB. Detectability of interaural delay in high-frequency complex waveforms. Journal of the Acoustical Society of America 1974;55:84–90. [PubMed: 4815755]

Javer AR, Schwarz DW. Plasticity in human directional hearing. Journal of Otolaryngology 1995;24:111–117. [PubMed: 7602671]

Laback B, Pok SM, Baumgartner WD, Deutsch WA, Schmid K. Sensitivity to interaural level and envelope time differences of two bilateral cochlear implant listeners using clinical sound processors. Ear and Hearing 2004;25:488–500. [PubMed: 15599195]

Lawson DT, Wilson BS, Zerbi M, van den Honert C, Finley CC, Farmer JC Jr, McElveen JT Jr, Roush PA. Bilateral cochlear implants controlled by a single speech processor. American Journal of Otology 1998;19:758–761. [PubMed: 9831150]

Lawson, DT.; Wolford, RD.; Brill, S.; Schatzer, R.; Wilson, BS. Speech processors for auditory prostheses. Twelfth Quarterly Progress Report (NIH Project N01-DC-8-2105); 2001.

Levitt H. Transformed up-down methods in psychoacoustics. Journal of the Acoustical Society of America 1971;49:467–477. [PubMed: 5541744]

Liberman MC. The cochlear frequency map for the cat: Labeling auditory-nerve fibres of known characteristic frequency. Journal of the Acoustical Society of America 1982;72:1441–1449. [PubMed: 7175031]

Loeb GE, White MW, Merzenich MM. Spatial cross-correlation. A proposed mechanism for acoustic pitch perception. Biological Cybernetics 1983;47:149–163. [PubMed: 6615914]

Long CJ, Carlyon RP, Litovsky RY, Downs DH. Binaural unmasking with bilateral cochlear implants. Journal of the Association for Research in Otolaryngology 2006;7:352–360. [PubMed: 16941078]

Long CJ, Eddington DK, Colburn HS, Rabinowitz WM. Binaural sensitivity as a function of interaural electrode position with a bilateral cochlear implant user. Journal of the Acoustical Society of America 2003;114:1565–1574. [PubMed: 14514210]

Markides, A. Binaural hearing aids. London; New York: Academic Press; 1977.

McFadden D, Pasanen EG. Binaural beats at high frequencies. Science 1975;190:394–396. [PubMed: 1179219]

McFadden D, Pasanen EG. Lateralization at high frequencies based on interaural time differences. Journal of the Acoustical Society of America 1976;59:634–639. [PubMed: 1254790]

Middlebrooks JC, Bierer JA, Snyder RL. Cochlear implants: the view from the brain. Curr Opin Neurobiol 2005;15:488–493. [PubMed: 16009544]

Moore DR, Hine JE, Jiang ZD, Matsuda H, Parsons CH, King AJ. Conductive hearing loss produces a reversible binaural hearing impairment. Journal of Neuroscience 1999;19:8704–8711. [PubMed: 10493771]

Mossop JE, Culling JF. Lateralization of large interaural delays. Journal of the Acoustical Society of America 1998;104:1574–1579. [PubMed: 9745740]

Neutzel JM, Hafter ER. Lateralization of complex waveforms: Spectral effects. Journal of the Acoustical Society of America 1981;69:1112–1118.

Nopp P, Schleich P, D'Haese P. Sound localization in bilateral users of MEDEL COMBI 40/40+ cochlear implants. Ear and Hearing 2004;25:205–214. [PubMed: 15179112]

Plomp R, Mimpen AM. Effect of orientation of the speaker's head and the azimuth of a noise on the speech reception threshold for sentences. Acustica 1981;48:325–328.

Poon PW, Hwang JC, Yu WY, Chan KH, Kwok PS. Detection of interaural time differences for clicks and tone pips: effects of interaural signal disparity. Hearing Research 1984;15:179–185. [PubMed: 6490544]

Rowan D, Lutman ME. Learning to discriminate interaural time differences: an exploratory study with amplitude-modulated stimuli. International Journal of Audiology 2006;45:513–520. [PubMed: 17005494]

Schroeder, MR. New viewpoints in binaural interactions. In: Evans, EF.; Wilson, JP., editors. sychophysics and Physiology of Hearing. New York: Academic Press; 1977. p. 455-467.

Shamma S, Klein D. The case of the missing pitch templates: how harmonic templates emerge in the early auditory system. Journal of the Acoustical Society of America 2000;107:2631–2644. [PubMed: 10830385]

Shamma SA, Shen NM, Gopalaswamy P. Stereausis: binaural processing without neural delays. Journal of the Acoustical Society of America 1989;86:989–1006. [PubMed: 2794252]

Simon HJ, Collins CC, Jampolsky A, Morledge DE, Yu J. The measurement of the lateralization of narrow bands of noise using an acoustic pointing paradigm: the effect of sound-pressure level. Journal of the Acoustical Society of America 1994;95:1534–1547. [PubMed: 8176057]

Smith-Olinde L, Besing J, Koehnke J. Interference and enhancement effects on interaural time discrimination and level discrimination in listeners with normal hearing and those with hearing loss. American Journal of Audiology 2004;13:80–95. [PubMed: 15248807]

Stellmack MA, Viemeister NF, Byrne AJ. Monaural and interaural intensity discrimination: level effects and the “binaural advantage”. Journal of the Acoustical Society of America 2004;116:1149–1159. [PubMed: 15376680]

Strickland EA, Viemeister NF, Fantini DA, Garrison MA. Within-versus cross-channel mechanisms in detection of envelope phase disparity. Journal of the Acoustical Society of America 1989;86:2160–2166. [PubMed: 2600306]

van de Par S, Kohlrausch A. A new approach to comparing binaural masking level differences at low and high frequencies. Journal of the Acoustical Society of America 1997;101:1671–1680. [PubMed: 9069634]

van de Par S, Kohlrausch A. Dependence of binaural masking level differences on center frequency, masker bandwidth, and interaural parameters. Journal of the Acoustical Society of America 1999;106:1940–1947. [PubMed: 10530018]

van Hoesel R, Ramsden R, Odriscoll M. Sound-direction identification, interaural time delay discrimination, and speech intelligibility advantages in noise for a bilateral cochlear implant user. Ear and Hearing 2002;23:137–149. [PubMed: 11951849]

van Hoesel RJ. Exploring the benefits of bilateral cochlear implants. Audiology and Neuro-Otology 2004;9:234–246. [PubMed: 15205551]

van Hoesel RJ. Sensitivity to binaural timing in bilateral cochlear implant users. Journal of the Acoustical Society of America 2007;121:2192–2206. [PubMed: 17471733]

van Hoesel RJ, Clark GM. Psychophysical studies with two binaural cochlear implant subjects. Journal of the Acoustical Society of America 1997;102:495–507. [PubMed: 9228813]

van Hoesel RJ, Tyler RS. Speech perception, localization, and lateralization with bilateral cochlear implants. Journal of the Acoustical Society of America 2003;113:1617–1630. [PubMed: 12656396]

Wightman FL, Kistler DJ. The dominant role of low-frequency interaural time differences in sound localization. Journal of the Acoustical Society of America 1992;91:1648–1661. [PubMed: 1564201]

Zwislocki J, Feldman RS. Just noticeable differences in dichotic phase. Journal of the Acoustical Society of America 1956;28:860–864.

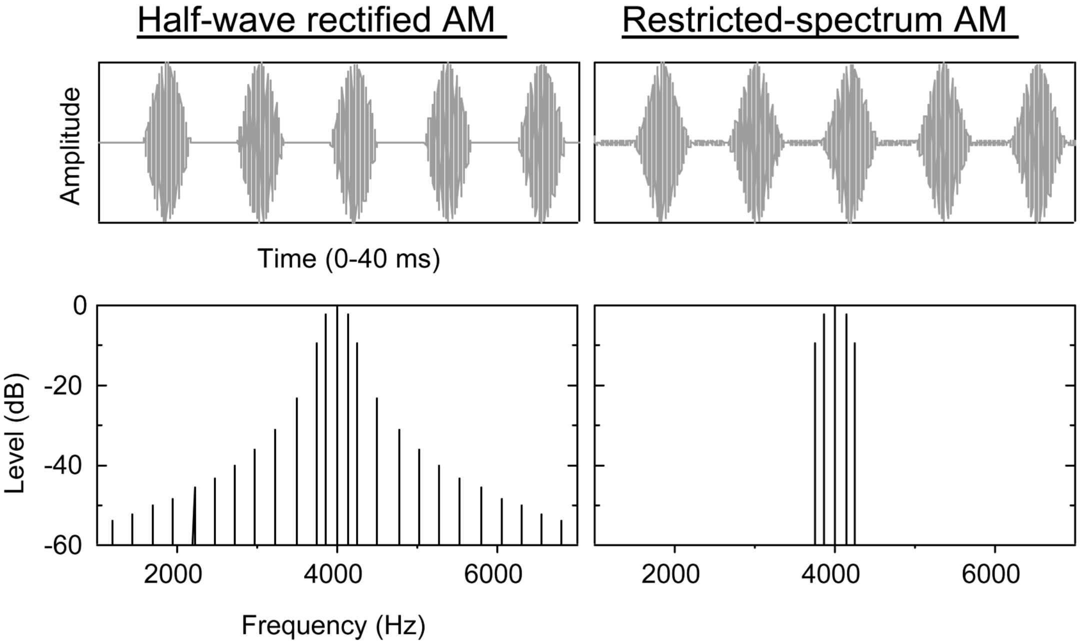

Figure 1.
Matched-carrier stimuli are illustrated in both the time and frequency domains, shown in the top and bottom panels, respectively. Panels on the left show the half-wave rectified AM stimulus, and those on the right show the effects of restricting the spectrum by removing all but 4 of the spectral sidebands.

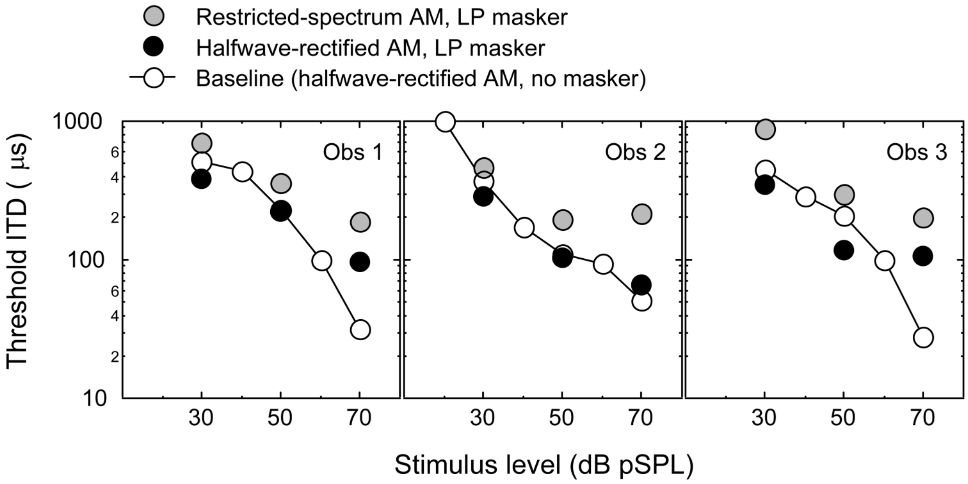

Figure 2.

The geometric mean of the ITD at threshold is plotted in μs as a function of peak stimulus level. Symbols indicate the condition, as described in the legend. Results for individual listeners are shown separately in each panel. Data for the 20 dB pSPL level are not shown for Observers 1 and 3 because thresholds exceeded the ceiling ITD of 1000 μs in those cases.

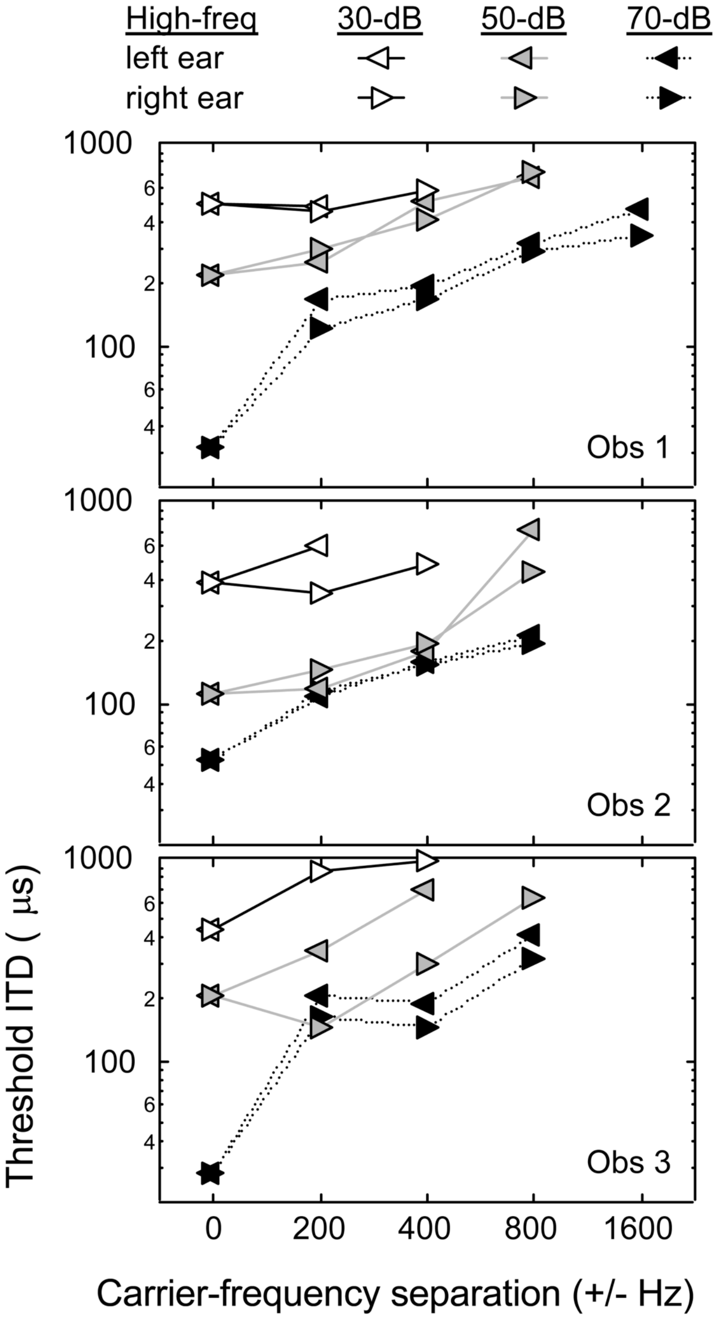

Figure 3.

The geometric mean of the ITD at threshold is plotted in μs as a function of carrier frequency mismatch across ears. Results for individual observers are shown in each panel. As indicated in the legend, the orientation of the triangle symbols indicates the ear receiving the higher frequency tone, either the right or the left, and shading indicates peak stimulus level. Thresholds exceeding the ceiling ITD of 1000 μs are not shown.

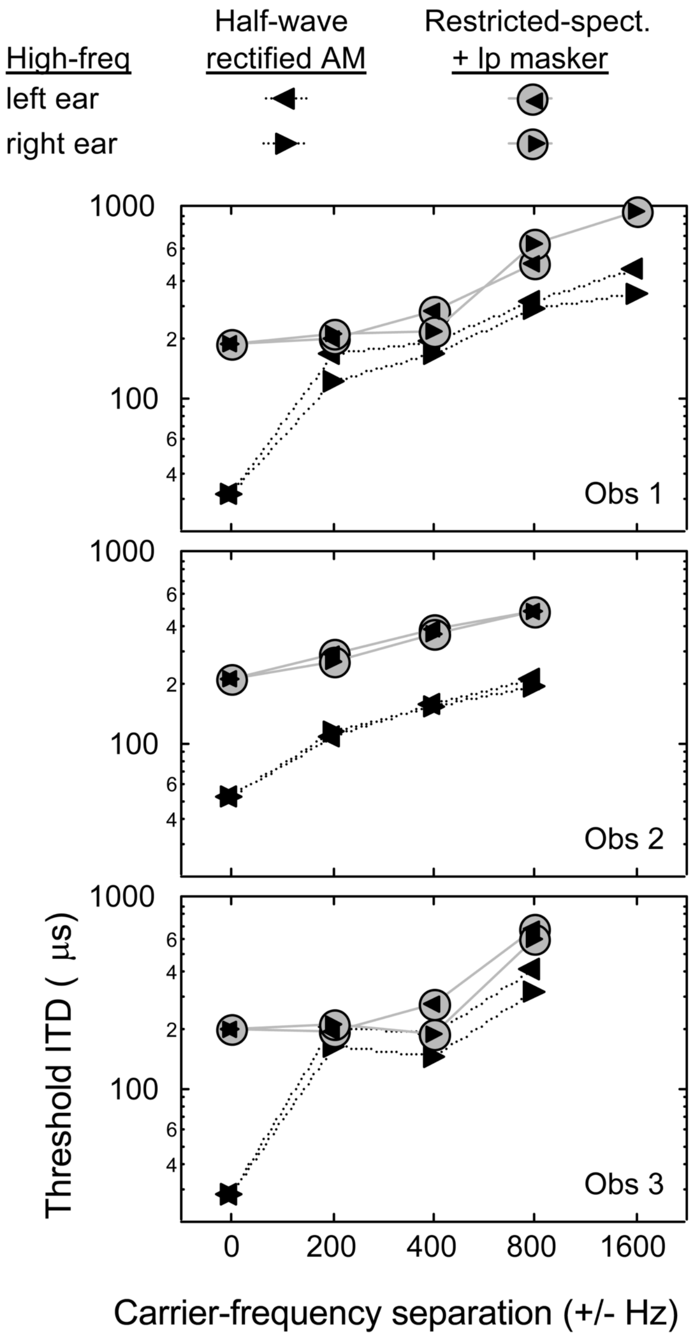

Figure 4.

The geometric mean of the ITD at threshold is plotted in μs as a function of carrier frequency mismatch across ears. Plain triangles show 70-dB pSPL data collected with the half-wave rectified AM stimulus, replotted from Figure 3. The symbols with a grey halo represent comparable conditions using a restricted-spectrum stimulus and a lowpass masker. As in Figure 3, left- and right-pointing triangles indicate conditions in which the ear receiving the higher frequency carrier was left or right, respectively.