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Discrimination of interaural temporal disparities conveyed by high-frequency sinusoidally amplitude-modulated tones and high-frequency transposed tones: Effects of spectrally-flanking noises

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Abstract

Dreyer and Oxenham (2008) reported that spectrally-flanking noise increased threshold-ITDs conveyed by high-frequency transposed tones but rendered them indiscriminable when they were conveyed by high-frequency sinusoidally amplitude-modulated (SAM) tones [Dreyer and Oxenham, J. Acoust. Soc. Am. **123**, EL1-EL7 (2008)]. This study extends those observations and evaluates the role of “off-frequency listening.” Threshold-ITDs were measured using 4 kHz-centered transposed or SAM tonal “targets.” In “baseline” conditions, targets were presented without spectrally-flanking noise. Additionally, targets were presented along with continuous diotic broadband Gaussian noise spectrally “notched” between 3.6 and 4.4 kHz. In another condition, only the high-pass segment of the notched noise was continuously present. In the final condition, only the low-pass segment was continuously present. Results indicate: 1) relative to baseline, adding notched noise resulted in similar relative increases of threshold-ITDs for both SAM and transposed targets; 2) the presence of the high-pass segment of the notched noise resulted in greater relative increases in threshold-ITDs over those obtained in baseline conditions for SAM tones as compared to transposed tones; 3) comparisons among all of the data were consistent with the interpretation that both on-frequency and off-frequency processing of envelope-based ITDs can be disrupted by the presence of a notched noise.

I. Introduction

Dreyer and Oxenham (2008) recently reported data concerning the discriminability of interaural temporal disparities (ITDs) conveyed by the envelopes of high-frequency stimuli.[1] The purpose of their study was to determine if the resolution of envelope-based ITDs depends upon listeners' use of “off-frequency” information (i.e., information in spectral regions surrounding those “tuned” to the center frequency of the stimulus). To that end, Dreyer and Oxenham measured threshold-ITDs using a two-alternative, forced-choice adaptive procedure and two classes of high-frequency complex waveforms: sinusoidally amplitude-modulated (SAM) tones and “transposed” tones. Transposed tones are specially constructed waveforms designed such that their envelopes convey temporal information to the high-frequency channels of the auditory system that is similar to that conveyed by low-frequency tones to the low-frequency channels of the auditory system (e.g., van de Par and Kohlrausch, 1997; Bernstein and Trahiotis, 2002).

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[1] We originally became aware of the principal findings of that study when they were presented at a meeting of the Association for Research in Otolaryngology (Dreyer et al., 2005). Subsequent to that meeting and well before formal publication in this Journal, both laboratories exchanged relevant information concerning the details surrounding their respective procedures and, more importantly, made each other aware of their empirical results. Especially helpful to the design of the present study was Ms. Dreyer's sharing of her Master's thesis.

Dreyer and Oxenham's (2008) general strategy was to evaluate off-frequency listening by comparing threshold-ITDs obtained when 4 kHz-centered targets were presented along with a diotic broadband noise containing a spectral “notch” between 3.6 and 4.4 kHz with threshold-ITDs obtained in the absence of such noise. They reported two interesting and important results. First, threshold-ITDs measured with transposed tones in the presence of the notched noise were elevated by a factor of two or so as compared to those measured in the absence of the surrounding noise. Second, for the SAM tones, adding the notched noise resulted in the listeners being unable to perform the task.

Being intrigued and perplexed by both of these findings, we conducted pilot studies with similar stimuli. In contrast to Dreyer and Oxenham's (2008) findings, we found that the presence of the notched noise did not make the task impossible when the ITDs were conveyed by the envelopes of SAM tones. Rather, our results indicated that the presence of a diotic notched noise resulted in similar increases in threshold-ITD for *both* transposed and SAM tones. Motivated by these informal findings, we decided to conduct a formal experiment. The goal was to obtain a set of data that would, in their totality, help to assess the effects of notched noise when listeners attempt to resolve envelope-based ITDs that are conveyed within high-frequency channels and to help to evaluate whether off-frequency listening is involved.

Two different types of explanation of Dreyer and Oxenham's (2008) and our preliminary findings occurred to us. The first explanation relies on “upward spread of masking” or “upward spread of excitation” (see Wegel and Lane, 1924; Egan and Hake, 1950; O'Malley and Feth, 1979; Schroeder et al., 1979 for relevant psychophysical data and Kim and Molnar; 1979 for relevant physiological data). Based on upward spread, spectral regions of the cochlear partition tuned to frequencies *above* 4 kHz would be expected to convey salient ITD-information that could enhance discrimination of ITDs by augmenting the ITD-information carried by the 4 kHz “target” region (see van de Par et al., 2000). If that were the case, then the high-pass segment of the notched noise could adversely affect performance by disrupting the use of ITD-information conveyed by those higher-frequency regions. There is also a manner in which upward spread of excitation could degrade performance. Specifically, the low-pass segment of the notched noise could disrupt ITD-information conveyed by the 4-kHz target region and, perhaps to some extent, ITD-information conveyed by regions of the cochlea tuned to frequencies above 4 kHz.

It is also logically possible that *downward* spread of excitation and *downward* masking could play a role. Assuming downward spread of excitation, then the presence of the low-pass segment of the notched noise could degrade sensitivity to ITD by preventing listeners from utilizing off-frequency ITD-information conveyed by spectral regions tuned *below* the 4-kHz target region. Again, assuming downward spread, the high-pass segment of the notched noise could disrupt ITD-information conveyed by the 4-kHz target region and, perhaps to some extent, ITD-information conveyed by spectral regions below 4 kHz.

We believe, however, that upward spread would affect ITD-processing more than would downward spread. This belief is based on two different types of psychophysical results. First, a variety of modern auditory masking studies (some of which are cited above) are consistent with the classic findings of Wegel and Lane (1924) and have demonstrated that masking is highly asymmetric in that a given masker produces a greater amount of masking for targets above its spectral region than for targets below its spectral region. For example, Schroeder et al. (1979) demonstrated that the masked threshold of a critical-band-wide noise centered at 1 kHz dropped at a substantially greater rate when the frequency of the 80-dB SPL tonal masker was raised above 1 kHz than when it was reduced below 1 kHz. Second, van de Par et al (2000), who also studied the use of off-frequency binaural information at high frequencies, found that it was off-frequency information in spectral regions *above* the signal that was salient for the discrimination of high-frequency, envelope-based ITDs.

II. Experiment

In order to evaluate these possibilities, threshold-ITDs were measured using SAM or transposed tonal “targets” centered at 4 kHz. All targets were 100% modulated at 128 Hz. Four general stimulus conditions were employed. In the first, or “baseline” condition, the targets were presented without spectrally-flanking noise. In the second condition, the targets were presented along with a continuous diotic broadband (10 kHz, low-pass) Gaussian noise having a spectral “notch” between 3.6 and 4.4 kHz. This stimulus condition is like the notched noise condition employed by Dreyer and Oxenham (2008). In the third condition, only the high-pass segment (4.4-10 kHz) of the notched noise was continuously present. In the fourth condition, only the low-pass segment (3.6 kHz low-pass) of the notched noise was continuously present.

A. Procedure

The SAM and transposed-tone targets were generated digitally using a sampling rate of 20 kHz (TDT AP2) and were low-pass filtered at 8.5 kHz (TDT FLT2). They were presented at 55, 75, or 85 dB SPL. The duration of the targets was 300 ms including 20-ms cos[2] rise-decay ramps. The spectrum levels of the notched, 4.4 kHz high-pass, and 3.6 kHz low-pass noises were each 35 dB below the respective level of the target (i.e., 20, 40, or 50 dB). This relative spectrum level was chosen to ensure that we employed a relative spectrum level that was no less than that used by Dreyer and Oxenham (2008). All of the noises, which were presented continuously during the experiment, were generated “off-line” in 1-hr segments using commercial software (Adobe Audition 1.5©) and were stored on compact discs. During the experiment, the noises were appropriately mixed with the target stimuli and presented to the listeners via TDH-39 earphones. When the baseline (no noise flanking the target) and 4.4-kHz high-pass noise conditions were employed, a continuous diotic noise, low-passed at 1.3 kHz (with a spectrum level −35 dB re the level of the target), was added to preclude listeners' use of low-frequency distortion products arising from normal, non-linear peripheral auditory processing (e.g., Nuetzel and Hafter, 1976;Bernstein and Trahiotis, 1994). Dreyer and Oxenham employed a diotic noise low-passed at 400 Hz toward a similar end.

Threshold-ITDs were measured using a two-cue, two-alternative, forced choice, adaptive task. Each trial consisted of a warning interval (500 ms) and four 300-ms observation intervals separated by 400 ms. Each interval was marked visually by a computer monitor. Feedback was provided for approximately 400 ms after the listener responded. The stimuli in the first and fourth intervals were diotic. The listener's task was to detect the presence of an ongoing ITD (left-ear leading) that was presented with equal *a priori* probability in either the second or the third interval. The remaining interval, like the first and fourth intervals, contained diotic stimuli. Ongoing ITDs were imposed by applying linear phase-shifts to the representation of the signals in the frequency domain and then gating the signals destined for the left and right ears coincidentally, after transformation to the time-domain. The starting phases of the envelopes and carriers of the targets were chosen randomly for each observation interval both within and across trials. The ITD for a particular trial was determined adaptively in order to estimate 70.7% correct (Levitt, 1971). The initial step-size for the adaptive track corresponded to a factor of 1.584 (equivalent to a 2 dB change of ITD) and was reduced to a factor of 1.122 (equivalent

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[2] Our choice of levels of the target (55, 75, and 85 dB SPL) was made in order to include data taken within the range of levels employed by Dreyer in her Master's thesis (30 to 80 dB SPL) and to include 75 dB SPL, a level often employed in our previous relevant investigations. The data formally reported by Dreyer and Oxenham (2008) and shown in our Fig. 2, represent a subset (40 to 70 dB SPL) of the levels utilized in Dreyer's Master's thesis.

to a 0.5 dB change of ITD) after two reversals. A run was terminated after 12 reversals and threshold was defined as the geometric mean of the ITD across the last ten reversals.

Four normal-hearing adults served as listeners. Two of the listeners (BT and KM) were highly sensitive to ITDs in the baseline condition and two others (RS and RC) were less sensitive. By comparing data obtained across both pairs of listeners it was possible to evaluate potential interactions between the effects produced by noise flanking the targets and baseline sensitivity to envelope-based ITDs. Particular stimulus combinations were chosen pseudo-randomly and three consecutive estimates of threshold were obtained for each of the 24 stimulus combinations (two types of target X four noise conditions X three levels) before moving on to the next one. Twelve estimates of threshold were obtained for each stimulus combination and the final values of threshold for each listener and stimulus combination were obtained by computing the median of those 12 estimates.

B. Results and discussion

1. Baseline and notched-noise conditions—The two plots in the top row of Figure 1 depict threshold-ITDs measured as a function of overall level for the transposed targets. The left and right panels depict average threshold-ITDs obtained from our two more-sensitive and our two less-sensitive listeners, respectively. Closed symbols represent the data obtained in the baseline condition; open symbols represent the data obtained when the targets were surrounded by a 3.6 - 4.4 kHz notched noise. The error bars represent ± one standard error of the mean. The small squares in the left panel represent average threshold-ITDs transcribed from Dreyer and Oxenham (2008)[2]. In the same fashion, the two plots in the bottom row of Fig. 1 depict the threshold-ITDs obtained when the targets were SAM tones.

The data obtained in both studies show that 1) the presence of the notched noise elevated thresholds over those obtained in the corresponding baseline conditions and 2) there was little or no effect of varying the overall level of the target in either the baseline or the notched-noise condition. Visual comparisons among the threshold-ITDs for transposed stimuli (top row, left-hand panel) reveal that Dreyer and Oxenham's (2008) listeners were substantially more sensitive than our more-sensitive listeners in the baseline condition but were only slightly more sensitive in the notched noise condition. The right-hand panel in the top row shows that the threshold-ITDs obtained from our two less-sensitive listeners in the baseline condition are about a factor of three greater than those obtained from our more-sensitive listeners. That difference notwithstanding, the presence of the notched noise elevated thresholds by about a factor of two to three over those measured in the baseline condition, just as was the case for our more-sensitive listeners.

We now turn to the data collected with SAM stimuli (bottom row). In the baseline condition, threshold-ITDs obtained with SAM stimuli were very similar for Dreyer and Oxenham's (2008) listeners and for our more-sensitive listeners (left-hand panel). As was the case for the transposed stimuli (top row), our less-sensitive listeners' thresholds for SAM stimuli (right-hand panel) were approximately three times those of the more-sensitive listeners. In the presence of the notched noise, both our more-sensitive and our less-sensitive listeners required a doubling to tripling of ITD in order to reach threshold, just as was found with the transposed stimuli. This outcome differs greatly from Dreyer and Oxenham's as their listeners were unable to discriminate ITDs conveyed by SAM tones in the presence of the notched noise (indicated by the upward arrows atop the squares in the left-hand panel).

The data in Fig. 1 were subjected to a three-factor (two noise conditions X three overall levels X two stimulus types), within-subjects analysis of variance. The error terms for the main effects and for the interactions were the interaction of the particular main effect (or the particular interaction) with the subject “factor” (Keppel, 1973). Consistent with visual inspection of the data: 1) the main effect of noise condition (presence or absence of the notched noise) was significant (assuming an α of 0.05) [F(1,3) = 18.5, p = 0.02]; 2) the main effect of stimulus type (SAM or transposed) was also significant [F(1,3) = 15.0, p = 0.03]; 3) neither the main effect of overall level nor any of the interactions among the factors was significant.

Thus, the results of our formal experiment are in accord with the results of the pilot experiment that motivated this study in that threshold-ITDs are elevated relatively similarly for both high-frequency SAM and transposed tones. Potential factors that might account for the discrepancy between Dreyer and Oxenham's and our results will be discussed in section III.

2. Potential role of off-frequency listening—Each row of panels in Figure 2 displays data obtained from a pair of listeners. The particular pairings were chosen because they reflect a similar patterning of the data across conditions. As it turned out, each such pairing (BT/RS and KM/RC) consists of one of the more-sensitive listeners (BT or KM) and one of the less-sensitive listeners (RS or RC). The bars within each plot represent, for each listener, threshold-ITDs normalized against the mean threshold-ITD obtained in the respective SAM (left-hand panels) or transposed (right-hand panels) target baseline conditions. The data were collapsed across all three levels of presentation of the targets (55, 75, and 85 dB SPL). The error bars atop each bar within each plot represent the standard error of the mean calculated across all three levels of the stimuli. The small size of the error bars reflects the finding that the relative effects found with the low-pass and high-pass segments, like those analyzed statistically for the notched noise condition (Fig. 2) also did not vary appreciably with level.

Comparisons among the threshold-ITDs obtained from the four listeners in the conditions shown in Fig. 3 were evaluated via one-tailed paired t-tests utilizing an alpha of 0.05.

i. High-pass segment of the notched noise: Recall that, because of upward spread of excitation of the energy of the target, spectral regions of the cochlea tuned *above* 4 kHz could carry salient ITD-information that could augment ITD-information carried by the 4-kHz region. If that were the case, then the high-pass segment of the notched noise would adversely affect performance by disrupting the use of such information. In fact, for SAM targets, the data from all four listeners indicate that the presence of the 4.4-kHz high-pass noise increased threshold-ITDs by a factor of about 1.5-2.0 over those measured in the baseline conditions. Across the four listeners, thresholds-ITDs obtained with the high-pass segment were significantly larger than their baseline counterparts for SAM tones (t=5.6, df=11,p<0.0005). To the degree that upward spread of excitation of the target information plays a greater role than downward spread of excitation of the high-pass segment of the noise into the target region, this outcome is consistent with the listeners' use of an off-frequency listening strategy in the SAM baseline condition.

When the targets were transposed tones, however, the threshold-ITDs obtained from listeners BT and RC were essentially equal to those obtained in the baseline condition while those obtained from listeners RS and KM were elevated by about a factor of 1.25 over those obtained in the baseline condition. In this case, across the four listeners, thresholds-ITDs obtained with the high-pass segment were not significantly larger than their baseline counterparts tones (t=1.3, df=11, p=0.11). This lack of statistical significance could reflect 1) that the two pairs of listeners employed different strategies; 2) that, overall, there truly is no substantial effect produced by the addition of the high-pass segment when transposed tones serve as targets, or 3) that there is an effect produced by the high-pass segment but data from only four listeners do not yield sufficient statistical power to reveal it.

These statistical outcomes notwithstanding, visual inspection suggests that the relative increases in threshold-ITDs as compared to baseline in the presence of the high-pass segment that did occur were larger for SAM tones than for transposed tones. Those differences were found to be statistically significant via a two-tailed t-test (t=4.1, df=11, *p*=0.002). This finding suggests that ITD-information conveyed by spectral regions tuned above the center frequency of the target is not necessary for a listener to show enhanced processing of ITDs found with high-frequency transposed stimuli vs. SAM tones in the baseline conditions.

ii. Low-pass segment of the notched noise: Under the assumption that upward spread of excitation is more salient than is downward spread, the evaluation of deleterious effects attributable to only the low-pass segment of the notched noise is a bit more complicated than was the case for the high-pass segment. This is so because presenting only the low-pass segment of the notched noise along with the target could allow the listener to use “off-frequency” ITD-information within cochlear regions tuned well above 4 kHz. That listening strategy would diminish, if not eliminate, deleterious effects on ITD-processing stemming from upward spread of excitation of the low-pass segment's energy into the 4-kHz spectral region. Of course, such a strategy could not be usefully employed in the notched-noise condition because of the presence of the high-pass segment. Therefore, increases in threshold-ITD over the baseline condition produced by the presence of only the low-pass segment of the notched noise are likely to represent underestimates of the deleterious effects produced by that segment when it is accompanied by the high-pass segment in the notched noise condition.

Returning to the data in Fig. 2 with these notions in mind, note that, for SAM tones, listener BT's and listener RS's threshold-ITDs increased by a factor of about 1.5 over those measured in the baseline condition when the targets were presented along with the 3.6 kHz low-pass segment. In contrast, threshold-ITDs for listeners KM and RC did not increase. These differential outcomes notwithstanding, across the four listeners, thresholds-ITDs obtained with the low-pass segment were significantly larger than their baseline counterparts (t=2.2, df=11, p=0.024).

The data are consistent with the hypothesis that listeners KM and RC were better able to utilize an off-frequency listening strategy than were listeners BT and RS in order to “escape” deleterious effects from upward spread of excitation of the low-pass segment of the notched noise into the 4-kHz target region. In order for that hypothesis to be valid, it would be necessary to show that the low-pass segment of the notched noise, in and of itself, degrades sensitivity to ITDs. The fact that threshold-ITDs measured in the notched noise condition are significantly larger than those measured in the presence of either its low-pass (t=3.6, df=11, p=0.002) or its high-pass segment (t=2.2, df=11, p=0.027) provides the required support. This is so because if the low-pass segment of the notched noise had no effect, then threshold-ITDs obtained with the notched noise and with its high-pass segment would be equivalent. Instead, the notched noise increased threshold-ITDs significantly more so than did only its high-pass segment.

The data in Fig. 2 indicate that, for transposed tones, the presence of the low-pass segment of the notched noise elevated threshold-ITDs for listeners BT, RS and RC by factors of 1.45, 1.46, and 1.32, respectively, over those measured in the baseline condition. For listener KM, threshold-ITD increased by only 1.13. As was true for SAM tones, across the four listeners, thresholds-ITDs obtained with the low-pass segment were significantly larger than their baseline counterparts (t=2.1, df=11, p=0.028). Also, as was true for SAM tones, threshold-ITDs obtained with the notched noise were, for all four listeners, significantly larger than those obtained in the presence of either the low-pass (t=2.4, df=11, p=0.016) or the high-pass segments (t=5.4, df=11, p<0.0005) in isolation. Thus, following the same lines of reasoning presented above for SAM tones, the data are consistent with the hypothesis that all four listeners employed an off-frequency listening strategy to escape deleterious effects of the low-pass segment when it was presented in isolation.

III. General Discussion

As did Dreyer and Oxenham (2008), we found that the presence of a notched noise that spectrally flanked the high-frequency spectral region conveying ITD-information resulted in increases in threshold-ITD as compared to baseline conditions. In addition, we were able to confirm their finding that threshold-ITDs were essentially unaffected by changes in the overall level of the stimuli over a 30-dB range. On the other hand, some of the results of this investigation and the conclusions based on them differ from some of those of Dreyer and Oxenham.

The most striking difference between the studies is that, while none of Dreyer and Oxenham's (2008) listeners was able to perform the ITD-discrimination task with SAM tones in the presence of notched noise, all of our listeners (i.e., those in the formal study and those in the pilot study) were able to do so. In fact, we found that the notched noise produced about the same relative increase in ITD-thresholds for both SAM and transposed tones over their respective baseline conditions. In attempts to reconcile the differences between the two studies, we collected ancillary data using a two-interval forced-choice procedure like that employed by Dreyer and Oxenham and a pulsed notched noise which, like theirs, was gated on 400 ms before the first observation interval and gated off 200 ms after the second observation interval that composed a trial. The data in Fig. 1 were validated in that, even with these stimulus conditions and with no additional “practice,” all four of our listeners performed the task with both SAM and transposed tones and the group's threshold-ITDs were not appreciably different from those reported within the main experiments. In a final manipulation, the spectrum level of the notched noise was increased by 10 dB while leaving unaltered the levels of the SAM and transposed targets. Three of the four listeners participated in this follow-up study. All three of them were unable to perform the task (ITDs less than or equal to 1 ms could not be reliably discriminated). This outcome also suggests that the notched noise degrades the processing of ITDs similarly for SAM and transposed tones. At this time, we can offer no explanation for Dreyer and Oxenham's listeners' inability to process ITDs conveyed by SAM tones in the presence of notched noise while being able to do so for the transposed tones.

Another difference between the two studies concerns potential explanations for why the presence of the notched noise increases threshold-ITDs for both SAM and transposed tones. Dreyer and Oxenham (2008) interpreted those increases as resulting solely from a loss of “off frequency” ITD-information conveyed by spectral regions of the cochlear partition tuned either above or below the “on-frequency” 4-kHz region. Based on the notion that upward spread of excitation is greater than is downward spread of excitation, we suggest instead, or at least in addition, that increases in threshold-ITD produced by notched noise may reflect an upward spread of energy from the low-pass segment of the noise into, and perhaps above, the 4-kHz target region.

At this time, we know of no psychophysical evidence to counter the parsimonious view that off-frequency listening, when it does occur for the discrimination of ITDs within high-frequency SAM and transposed tones, relies on the use of ITD-information present within spectral regions of the cochlear partition tuned to frequencies *above* the center frequency of the target. Said differently, at this time, there appears to be no compelling evidence that listeners use off-frequency ITD-information conveyed by spectral regions centered below the spectral locus of the target. By this, we certainly do not mean to imply that listeners absolutely cannot or do not utilize off-frequency ITD-information within regions tuned below the target region. In order to make strong, it would seem necessary to gather data concerning the relative contributions of off-frequency listening within spectral regions above or below the target frequency region in a variety of binaural tasks and with a variety of stimuli.

The levels of noise utilized in both studies were below those found by Dreyer and Oxenham (2008) that would be required to produce *monaural masking* via upward spread of the energy of the low-pass segment into the on-frequency auditory filter containing the target. The absence of monaural masking, however, does not necessarily preclude other types of on-frequency effects (e.g., dilution of binaural cues) that could disrupt the processing of ITDs. In our view, an inability to account for any on-frequency-based degradation of the processing of ITDs via masking should not, by default, be taken as evidence that listeners, normally, in baseline conditions employ off-frequency listening via ITD-information conveyed within cochlear regions tuned below the center frequency of the target.

IV. Summary and conclusions

Threshold-ITDs conveyed by the envelopes of high-frequency SAM and transposed tones were measured in baseline conditions and in the presence of spectrally flanking notched noise, the lower spectral segment of the notched noise or the upper spectral segment of the notched noise. The data indicate that 1) relative to baseline conditions, the presence of a notched noise resulted in similar relative increases of threshold-ITDs for both SAM and transposed targets; 2) the presence of the high-pass segment of the notched noise resulted in greater relative increases in threshold-ITDs over those obtained in baseline conditions for SAM tones as compared to transposed tones; 3) comparisons among all of the data suggest to us that both on-frequency and off-frequency processing of envelope-based ITDs can be disrupted by the presence of a notched noise.

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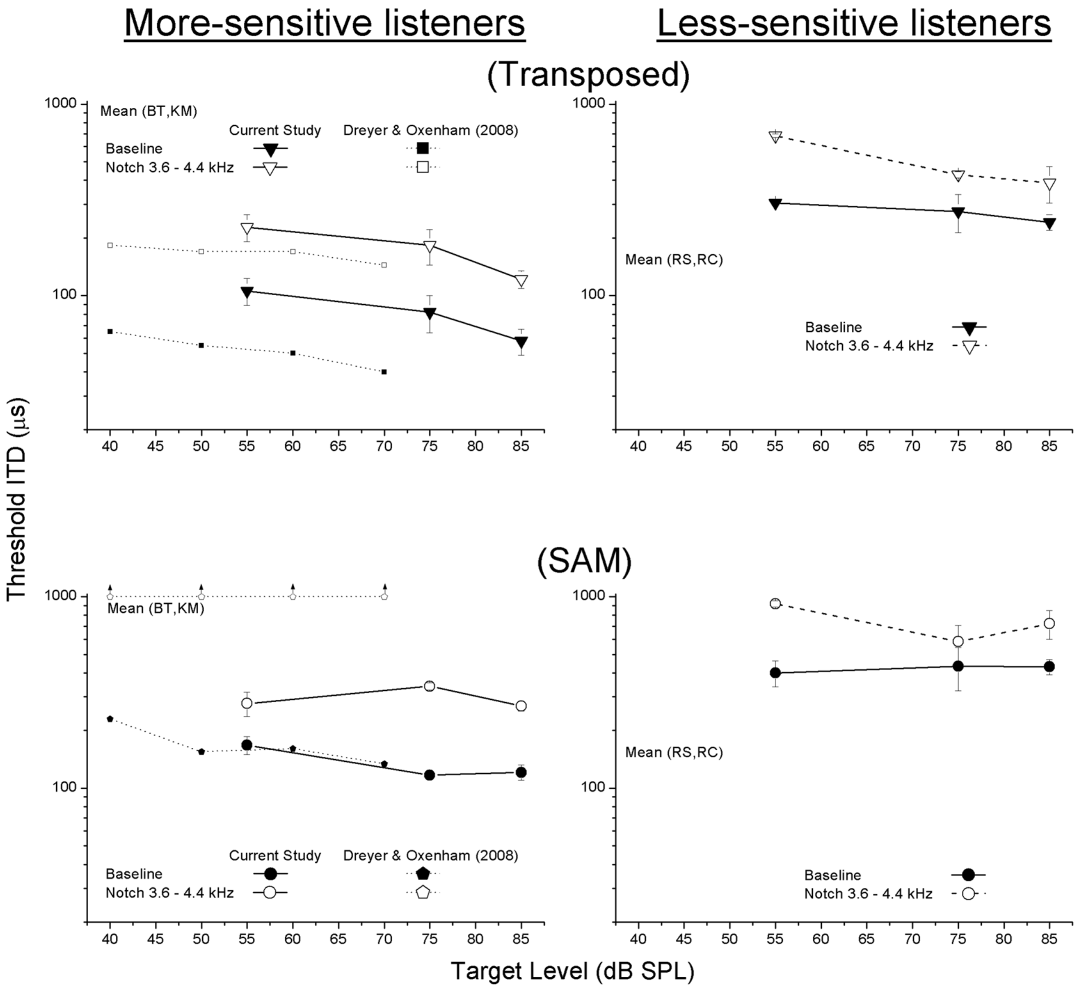

Figure 1.

Threshold-ITDs measured as a function of the overall level of the target. Left and right panels depict average threshold-ITDs obtained from the two more-sensitive and the two less-sensitive listeners, respectively. Panels in the top and bottom rows depict data obtained with the 4-kHz-centered transposed and SAM targets, respectively. The rate of modulation was 128 Hz. Closed symbols represent the data obtained in the baseline condition; open symbols represent the data obtained when the targets were surrounded by a 3.6 - 4.4 kHz notched noise. The error bars represent ± one standard error of the mean. The small squares in the left panel represent average threshold-ITDs transcribed from Dreyer and Oxenham (2008).

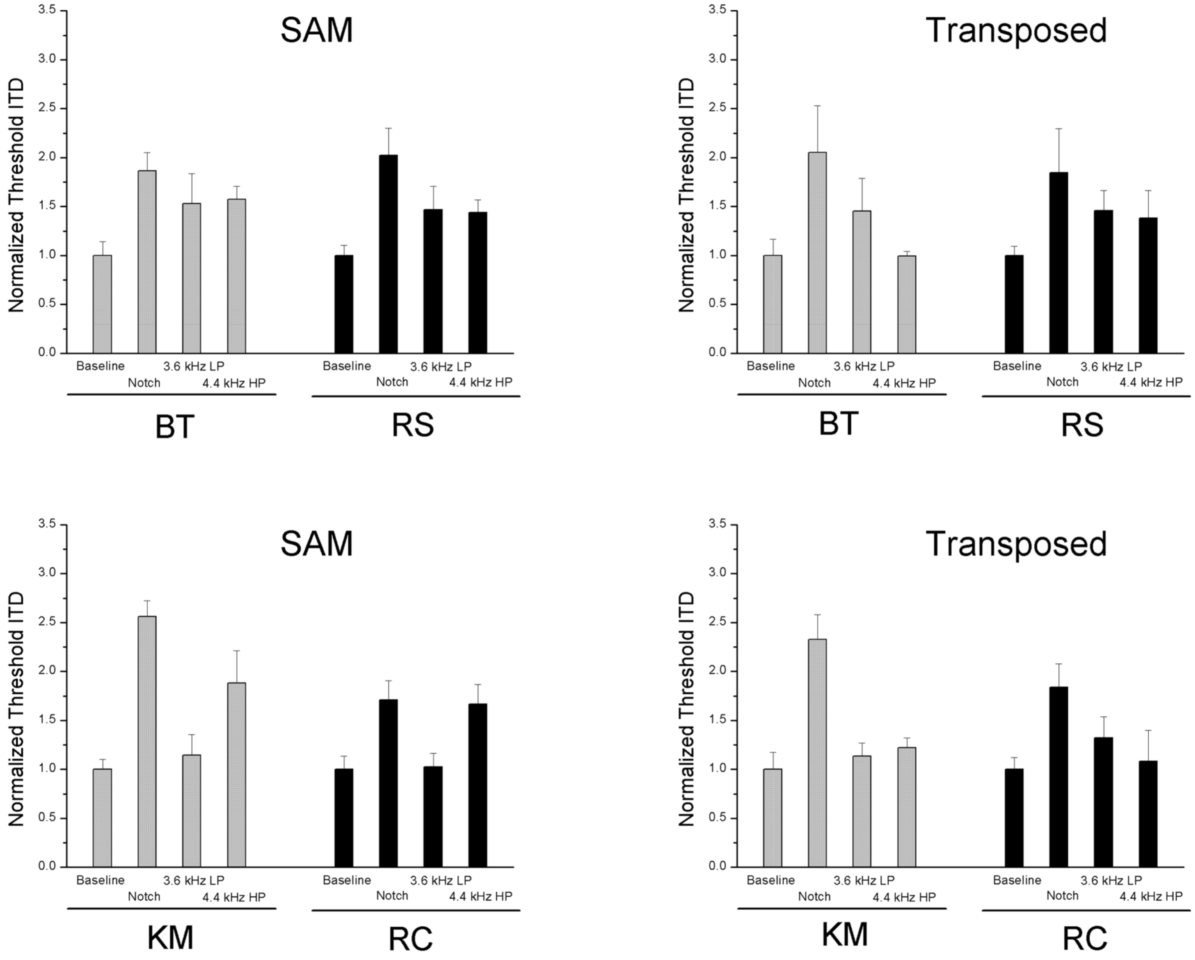

Figure 2.

Each row displays data obtained from a pair of listeners (BT/RS or KM/RC). The bars within each plot represent, for each listener, threshold-ITDs normalized against the mean threshold-ITD obtained in the respective SAM (left-hand panels) or transposed (right-hand panels) target baseline conditions. The data were collapsed across all three levels of presentation of the targets (55, 75, and 85 dB SPL). Error bars represent one standard error of the mean.