Localization of sound in rooms. V. Binaural coherence and human sensitivity to interaural time differences in noise

Brad Rakerd
Department of Communicative Sciences and Disorders, Michigan State University, East Lansing, Michigan 48824

William M. Hartmann[a)]
Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824

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Binaural recordings of noise in rooms were used to determine the relationship between binaural coherence and the effectiveness of the interaural time difference (ITD) as a cue for human sound localization. Experiments showed a strong, monotonic relationship between the coherence and a listener's ability to discriminate values of ITD. The relationship was found to be independent of other, widely varying acoustical properties of the rooms. However, the relationship varied dramatically with noise band center frequency. The ability to discriminate small ITD changes was greatest for a mid-frequency band. To achieve sensitivity comparable to mid-band, the binaural coherence had to be much larger at high frequency, where waveform ITD cues are imperceptible, and also at low frequency, where the binaural coherence in a room is necessarily large. Rivalry experiments with opposing interaural level differences (ILDs) found that the trading ratio between ITD and ILD increasingly favored the ILD as coherence decreased, suggesting that the perceptual weight of the ITD is decreased by increased reflections in rooms.
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I. INTRODUCTION

This article is the fifth in a series of articles about localization of sound in rooms by human listeners (see Hartmann and Rakerd, 1989, for references). It is particularly concerned with localization as cued by a steady-state interaural time difference (ITD). If a sound source is off to the left or right of a listener, the sound will reach the listener's near ear sooner than the far ear and thus lead in time. For an extreme lateral position—a source directly left or directly right of the listener in free field—the ITD can be larger than 700 μs. For smaller angles, the ITD is smaller, but listeners are able to make use of ITDs as small as 10 μs (Hershkowitz and Durlach, 1969).

Depending on the stimulus, localization information may arise from the ITD in the signal onset or in the steady state or both. If the stimulus is a noise band, as in the present study, steady-state cues play a dominant role (Tobias and Schubert, 1959; Guiguère and Abel, 1993). The nature of the steady-state spectrum is also important. At low frequencies, listeners are sensitive to ITD cues conveyed by the signal fine structure. At high frequencies, listeners are only sensitive to signal envelope cues (Leakey *et al.*, 1958; McFadden and Pasanen, 1978; Henning, 1974, 1980). The boundary between low and high is a region near 1300 Hz (Zwislocki and Feldman, 1956).

There is evidence that the fine-structure ITD is the dominant cue to source location when it is audible (Wightman and Kistler, 1992, Macpherson and Middlebrooks, 2002), but there is also evidence that a listener's sensitivity to the ITD may vary, depending on how similar the waveform shapes are in the two ears (Jeffress *et al.*, 1962; Trahiotis *et al.*, 2001). A statistical measure of this similarity is provided by the binaural cross-correlation, computed as a function of the time lag between the left and right ears. The maximum of this function within a restricted range of lags (typically ±1 ms or ±2 ms) is the binaural waveform coherence, to be called simply, the "coherence."

Under ideal listening conditions, in an anechoic environment (free field) with the listener facing the source of sound, the coherence will be very close to 1.0, no matter what the spectral structure of the noise might be. But when the inputs to a listener's ears become degraded by acoustical reflections from the surfaces of a room, the coherence will be smaller, possibly much smaller. In the limit of very small coherence, the ITD tends to lose its meaning in that there are no common waveform features that can be compared to identify an ITD.

Figure 1 shows the coherence, measured with a manikin in a large room. Each point shows a measurement in a one-third octave band. Measurements were averaged over 10 different positions of the source, all 12 m from the manikin (Hartmann *et al.*, 2005). Except for very low frequencies, the coherence was quite far from 1.0. Moving the source closer to the manikin increased the coherence because the direct sound played a larger role compared to reflections, but the coherence never approached its value in free field.

This article presents experiments intended to describe the relationship between coherence, as it occurs in rooms,

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[a)] Author to whom correspondence should be addressed. Electronic mail: hartmann@pa.msu.edu

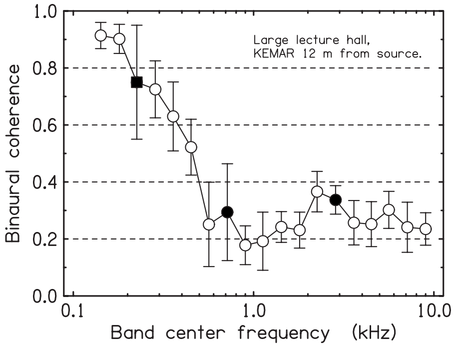

FIG. 1. Binaural coherence measured in a lecture hall for 1/3-octave noise bands. Measurements were made at 10 different locations within the room with a sound source (loudspeaker) and receiver (KEMAR) separated by 12 m. Symbols show the mean coherence; error bars are two standard deviations in overall length. Filled circles indicate the "mid" and "high" bands used in Experiments 1 and 2 of the present article. The filled square shows the "low" band used in Experiment 3.

and the ability of human listeners to use the ITD to discriminate the locations of noise bands. Experiment 1 tested the hypothesis that coherence alone is an adequate measure of a room to predict sound localization mediated by the ITD. According to this hypothesis, all other aspects of the room acoustics are irrelevant. Experiment 2 measured the perceptual weight that listeners attach to ITD cues, depending on the overall level of coherence. Finally, Experiment 3 measured listeners' sensitivity to the ITD for a noise band in the low-frequency region where the range of possible coherence values is both high and physically compressed.

II. EXPERIMENT 1: MID BAND AND HIGH BAND

Experiment 1 measured listeners' sensitivity to steady-state ITD cues in one-third octave noise bands as a function of coherence. The stimuli were binaural recordings made in three different rooms, differing by more than a factor of five in their reverberation times.

- Room 16 was a dry classroom of medium size with a volume of 216 m^3, with a carpet on the floor, acoustical tile on the ceiling, and some sound absorbing panels on the walls. The classroom was full of student desks. The reverberation time was 0.4 s at all experimental frequencies.
- Room 10 was a laboratory room ($v=219$ m^3) with cinder block walls, tile floor, and a high concrete ceiling. This room had desks and equipment distributed around its periphery and a large open space at the center. The reverberation time was 0.8 s.
- Room RR was an IAC reverberation room ($v=174$ m^3) with diffusing panels mounted along the sidewalls. The reverberation time varied from 1.2 s at low experimental frequencies to 2.5 s at high. Additional details for all of these rooms can be found in Hartmann *et al.* (2005).

A second factor of interest in this experiment was the spectra of the noise bands themselves. As noted above, the character of ITD cues changes somewhere near 1300 Hz. With this in mind, recordings were made of noise in two different frequency bands: a mid-band with all frequency components well below 1300 Hz and a high-band with all components well above 1300 Hz.

A. Methods

1. Listeners

There were five listeners in Experiment 1. Four listeners (S1-S4) were young adults (ages 17–23) with pure-tone thresholds for both ears within normal limits from 125 to 8000 Hz. The fifth listener (S5) was the first author, age 56, with normal hearing thresholds out to 4000 Hz and mild hearing loss at higher frequencies. All listeners were male except for S1.

2. Stimuli

The stimuli for Experiment 1 were noise bands with a 1/3-octave rectangular frequency spectrum. The mid-band noise had a center frequency of 715 Hz and lower and upper edge frequencies of 630 and 800 Hz. The high band was two octaves higher, with a center frequency at 2850 Hz and edge frequencies of 2500 and 3200 Hz. Recordings of the mid-band and the high-band noises were made in each of the three rooms described above.

A KEMAR manikin (Burkhard and Sachs, 1975) and a loudspeaker sound source (McIntosh ML-1C) were placed at nonspecial locations in the three rooms as needed in order to gather: (a) a set of seven mid-band recordings that featured target coherence values of 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8; and (b) a set of seven high-band recordings that featured those same coherence values. A recording was accepted as having a coherence that matched one of the target values if the measured coherence deviated from the target by no more than 0.025. The only other constraint on the selection of these recordings was that the cross-correlation peak had to occur at a lag (ITD) within the range from −60 to +60 μs, corresponding to a sound source location that is within 4° of straight ahead.

The KEMAR always faced the loudspeaker, and the distance between them was varied as needed in each room in order to obtain full sets of mid-band and high-band recordings. In the most reverberant environment (Room RR), the distance had to be reduced to as little as 41 cm in order to make recordings with the highest coherence values required for the experiment. In the least reverberant environment (Room 16), the distance had to be extended as far as 900 cm to make recordings with the lowest required coherences.

The recorded sounds were presented to listeners by headphones. To focus attention on the ITDs, any interaural level differences present in the KEMAR recordings were digitally eliminated by setting the levels of both left and right channels equal to 70 dB SPL. The overall duration of a noise stimulus was 1 s, and it was turned on and off slowly (200-ms raised-cosine envelopes) to eliminate transient localization cues.

3. Interaural time differences

To find the just detectable ITD, the controlling computer introduced interaural time differences of different durations,

Δt. Pilot testing showed that listeners were more sensitive to Δt in mid-band signals than in high-band signals. Accordingly, on mid-band runs, perceptual testing was done with $\Delta t = 25$, 75, 125, and 175 μs, and on high-band runs testing was done with $\Delta t = 200$, 300, 400, and 500 μs.

4. Listening runs

Listening runs were blocked by frequency range and by room. Hence on each run a listener was presented a set of mid-band noises or a set of high-band noises that had been recorded in one of the three rooms. A run included 56 trials, eight presentations of each of the seven coherence values that comprised a full noise-band set. The eight presentations consisted of two at each of the four values of Δt that were applicable for a mid-band or high-band test. The order in which the individual trials of a run took place was completely random on every run. Altogether a listener completed 60 runs—ten mid-band runs and ten high-band runs for each of the three rooms. The order in which these runs were carried out was random and different for every listener.

5. Testing procedure

The listeners were tested individually while seated in a quiet room. On each trial, a noise band stimulus was presented twice. On the first presentation, the stimulus was played with the interaural time characteristics of the ILD-equalized KEMAR recording—peak lag magnitude less than or equal to 60 μs. On the second presentation, an added ITD, Δt, was introduced by digitally delaying one of the channels. On half of the trials (selected at random) the left channel was delayed, which corresponded to a shift of the sound source to the right, and on the other half the right channel was delayed, which corresponded to a shift to the left. The listener's task was to decide whether the image moved left or right on the second presentation and to report the decision to the experiment computer by means of a response box.

B. Mid-band results

Figure 2 shows the percentage of consistent responses for the mid-band noises, i.e., the percentage consistent with the direction of the added ITD (McFadden *et al.*, 1973). The means, averaged over the five listeners, are plotted as a function of the ITD parameter, Δt. The error bars are two standard errors in overall length, i.e., overall length $=$standard deviation$\times 2/\sqrt{5}$. There is a separate plot for each of the seven different values of coherence (0.2 through 0.8).

A first observation about these results is that performance increased regularly with increasing values of the ITD. A second is that performance also increased regularly with increasing coherence at every value of the ITD tested. A two-factor (repeated measures) analysis of variance (ANOVA) confirmed the statistical significance of both of these effects [ITD: $F(3,12)=114.5$; $p<0.001$; coherence: $F(6,24)=78.3$; $p<0.001$]. The interaction of ITD with coherence was also significant [$F(18,72)=5.4$; $p<0.001$], reflecting the fact that slopes of the psychometric functions differed depending on the overall level of coherence.

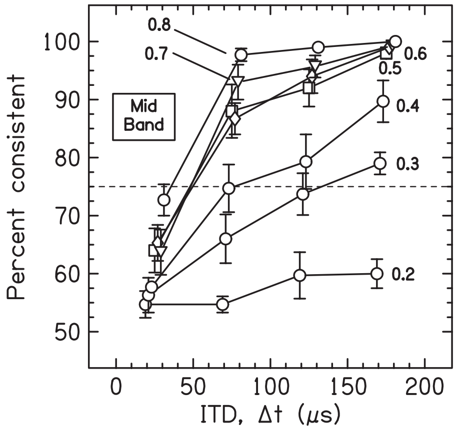

FIG. 2. Results of Experiment 1 for the mid-frequency noise band (715 Hz). The percentage of lateralization judgments consistent with the sign of the applied interaural time difference (ITD), averaged over the five listeners, is plotted as a function of the ITD with noise band coherence as a parameter. Symbols have been slightly jogged left and right for clarity, and different symbols are used occasionally to avoid confusion. Error bars are two standard errors in overall length.

Figure 2 shows the following characteristics depending on the coherence:

(a) *Coherence*=0.2: Listeners gained only a little ITD information from the mid-band noises with a coherence of 0.2. The psychometric function with a coherence of 0.2 in Fig. 2 was shallow and increased only slightly above chance level (50% consistent) at the longest added ITD tested. A coherence of 0.2 is an interesting target because the smallest values of coherence that Hartmann *et al.* (2005) measured in any room were just under 0.2.

(b) *Coherence*=0.3 *and 0.4*: The psychometric functions for coherence of 0.3 and 0.4 showed greater ITD sensitivity. Both functions grew steadily and approximately linearly with increasing values of the ITD. When coherence was 0.3, the threshold (75%-consistent) was approximately 135 μs, which would allow a listener to identify an angular displacement of about 10° from the forward direction. With a coherence of 0.4 the threshold was approximately 75 μs, corresponding to a displacement of about 6°. Both of these values are well above the horizontal plane difference limen of about 1° that can be achieved with perfectly coherent signals in free field (Blauert, 1996), but the accuracy is sufficient to be of practical value when listening in a room.

(c) *Coherence*=0.5 *or greater*: The psychometric functions for a coherence of 0.5 or greater all rose steeply as a function of the ITD and reached nearly 100% consistent for the longest added ITDs tested. The 75%-consistent threshold estimates for these functions were all less than 50 μs, and for a coherence of 0.8, the highest coherence tested here, the threshold was less than 30 μs, corresponding to a displacement of about 2°.

C. High-band results

Figure 3 shows the results of the experiment for the high band. Again, there was a strong tendency for performance to

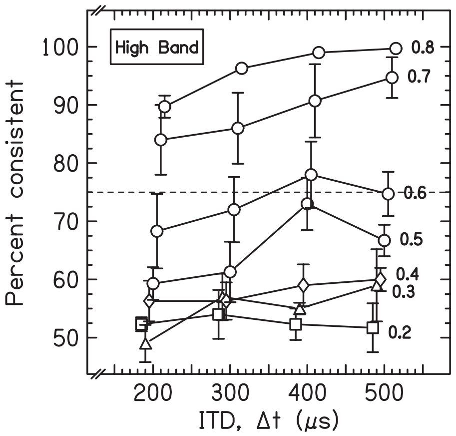

FIG. 3. Same as Fig. 2 except for the high-frequency noise band (2850 Hz).

increase with both the ITD and the coherence, and ANOVA confirmed the statistical significance of both of these effects [ITD: $F(3,12)=6.5$, $p<0.01$; coherence: $F(6,24)=36.2$, $p<0.001$]. The interaction between these factors was not significant ($p>0.05$). Results for individual waveform coherence values, γ, are given below. Because of the importance of the envelope for localization of high-frequency noises, the envelope coherence γ_{env} is given in square brackets [...]. It is the maximum of the normalized correlation (Bernstein and Trahiotis, 1996), and was calculated from the formula $\gamma_{env} = \pi/4+(1-\pi/4)\gamma^{2.1}$ (Aaronson and Hartmann, 2010), which accounts for the fact that an envelope is never negative.

(a) *Coherence*=0.2 [0.79]: With a coherence of 0.2, there was no evidence that listeners could detect ITD information from the high band. To the contrary, the psychometric function in Fig. 3 was flat and near chance level, even though ITDs as large as 500 μs were presented.

(b) *Coherence*=0.3 *and 0.4* [0.80 and 0.82]: When the coherence reached 0.3 or 0.4, some ITD information may have been available, but not much. The psychometric functions were shallow but rising over the ITD range tested (200–500 μs).

(c) *Coherence*=0.5 *and 0.6* [0.84 and 0.86]: The psychometric functions for coherences of 0.5 and 0.6 rose with increasing ITD and appeared to reach threshold for an ITD of about 400 μs or greater. Thus, the ITD sensitivity for the high band with a coherence of 0.5 or 0.6 is roughly equivalent to the sensitivity seen for the mid band with coherence equal to 0.2. It could possibly support gross judgments about lateral position or about lateral movement, but could in no way allow for accurate localization.

(d) *Coherence*=0.7 *and 0.8* [0.89 and 0.92]: The high-band results for coherences of 0.7 and 0.8 revealed a much greater sensitivity than seen for lower values of coherence. Discrimination scores were above the 75%-consistent threshold level for all ITDs tested at both of these coherence levels. An extrapolation of the threshold point from the psychometric function leads to a threshold estimate of approximately 75 μs for coherence =0.7. This would support localization of the high-band noise to within 6 deg, which is comparable to the sensitivity seen with the mid band for coherence=0.4. The high-band threshold for coherence=0.8 could not be accurately estimated from the data in Fig. 3, but any estimate would clearly be below the threshold for a coherence of 0.7, possibly much below.

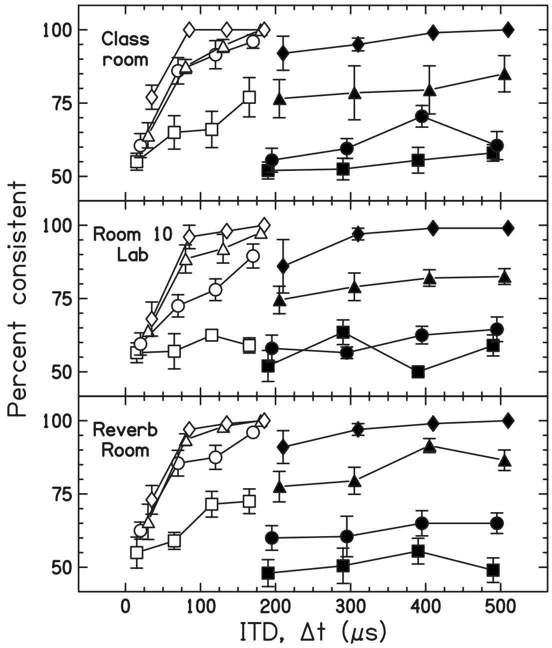

FIG. 4. Results of Experiment 1 for the mid band (open symbols) and the high band (filled symbols) separated out by room. Each plot corresponds to a different level of noise-band coherence (Squares: coherence=0.25. Circles: coherence=0.45. Triangles: coherence=0.65. Diamonds: coherence =0.80). Symbols have been slightly jogged left and right for clarity.

D. Room-by-room results

As noted above, the stimuli for Experiment 1 were recorded in three different rooms with very different acoustical characteristics. The reverberation times differed by a factor of five. To test the hypothesis that coherence alone predicts localizability, an analysis was done to see whether differences among the rooms were important to listeners' sensitivity to ITD and to coherence. Figure 4 shows the results of Experiment 1 plotted separately by room. Psychometric functions for the mid band are plotted with open symbols; functions for the high band are plotted with filled symbols. Data for neighboring values of coherence are averaged together in the plots as follows: The results for coherence =0.2 and 0.3 are combined and plotted as coherence=0.25 (squares). Similarly, 0.4 and 0.5 are combined (coherence =0.45, circles), and 0.6 and 0.7 are combined (coherence =0.65, triangles). Diamonds show the results for a coherence of 0.8.

In general, the results for the mid band were quite similar across all three rooms. The one notable exception was that the psychometric functions for coherence=0.25 and coherence=0.45 were both somewhat lower in Room 10 than in the other two rooms. For the high band, all of the coherence functions, and especially the functions with higher levels of coherence (coherence=0.65 and coherence=0.80), were very similar across the three rooms.

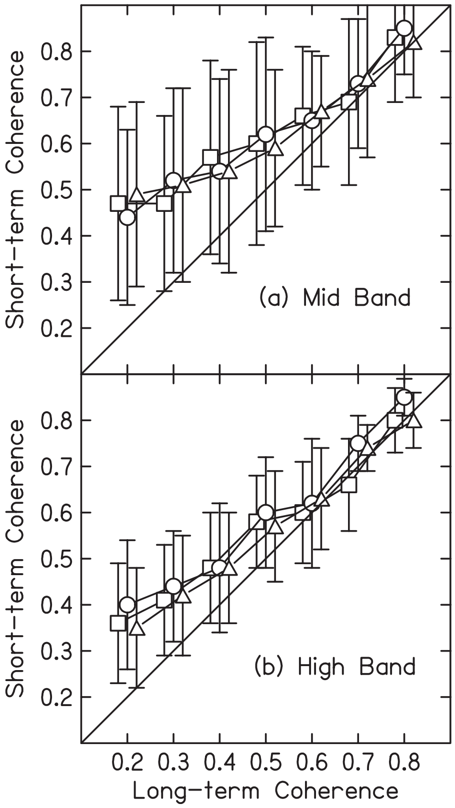

FIG. 5. Mean short-term coherence plotted as a function of the long-term coherence for three rooms. The error bars are two standard deviations in overall length. Squares are for the Classroom. Circles are for the Room 10 Laboratory. Triangles are for the Reverb Room.

ANOVAs run on both the mid-band results and the high-band results found no significant differences among the rooms ($p > 0.05$). Nor were there any significant interactions between room and ITD or room and coherence in either of the analyses ($p > 0.05$ in all cases). Hence, in general, physical differences among the rooms made little difference in the outcome of the experiment. The major determining factor was coherence, and it affected listeners approximately equally in all three room environments.

1. Short-term coherence

The room-by-room comparisons reported above are based on coherence values computed over the duration of an entire stimulus, a full second. However, it is possible that listeners make localization decisions on the basis of a series of short-term binaural analysis intervals, as studied by Shinn-Cunningham and Kawakyu (2003). These short-time coherence values might differ considerably from the long-term coherence. Moreover, they might differ across rooms in ways that could explain, at least in part, why Fig. 4 shows several instances in which listeners' ITD sensitivity varied somewhat from room to room. The stimuli of Experiment 1 were therefore re-analyzed with the coherence calculated for a series of short-time windows (20-ms window length, 10-ms overlap between neighboring windows, n=97 windows per stimulus).

Results for the mid band are given in Fig. 5(a); results for the high band are given in Fig. 5(b). When the long-term coherence is low, the short-term coherence means overestimate the corresponding long-term coherence, and the standard deviations are large. Both of these tendencies are somewhat greater for the mid-band than for the high band, as expected given the relative noise bandwidths.

Notably, for both bands, there were almost no differences among the plots for the three rooms, certainly none that relate to the perceptual results shown in Fig. 4. Similar room-by-room short-term comparisons were carried out for the ITD and the ILD, and they too showed very good agreement across rooms. We conclude that the listeners' responses in Experiment 1 were unlikely to have been influenced by any room-by-room variation in the short-time characteristics of a stimulus.

E. Mid band vs. high band

As might have been expected from the amplitude modulated tone lateralization experiments by Bernstein and Trahiotis (1985), the psychometric functions relating percent-consistent responses to ITD were pushed out to higher values of ITD and were much shallower functions for high frequencies compared to mid frequencies. These differences are particularly apparent in Fig. 4.

In the mid band, listeners showed some small ITD sensitivity at the very lowest level of coherence tested, coherence=0.2. For the high band, comparable performance did not appear until coherence had grown to 0.5 or 0.6. With respect to more detailed sensitivity, a threshold estimate of 75 μs was obtained for the mid band when coherence was 0.4; for the high band, a comparable threshold was not obtained until the coherence reached 0.7.

The surfaces of a room are normally more sound absorbing at high frequencies, which tends to increase the coherence of a high-band noise compared to the coherence of a mid-band noise. The results of the present experiment indicate that the increases in coherence with frequency would have to be substantial if they are to in any way improve a listener's ability to detect ITD information.

III. EXPERIMENT 2: TIME-INTENSITY TRADING

Classic headphone experiments on the lateralization of sounds gave listeners conflicting interaural level differences (ILD) and interaural time differences (ITD), to determine trading relationships (Moushegian and Jeffress, 1959; Domnitz and Colburn, 1977). Sounds in a room present the same kind of conflicting cues to the listener's two ears because standing waves in the room produce uncoordinated interaural differences. Experiment 2 measured a trade-off between steady-state ITD and ILD for different levels of coherence, including perfect coherence (i.e., coherence=1.0). Like Experiment 1, Experiment 2 measured the effectiveness of an ITD for both the mid band and the high band, but it did so in the presence of an added ILD.

In a previous study of sound localization in rooms, we found that steady-state ITD cues in a 500-Hz sine tone were discounted when those cues became implausible (Rakerd and Hartmann, 1985). In the present experiment with noise bands recorded in rooms, we hypothesized that the weighting of ITD would be discounted in instances where coherence was low. It is possible that a variation on the position variable model (see Stern and Shear, 1996) that accounted for coherence would make a similar prediction.

A. Methods

Five listeners participated in this experiment. Four of them (S1, S2, S3, and S5) had previously participated in Experiment 1. The fifth listener, S6, was new. S6 was a male listener, age 21, with normal hearing thresholds.

Experiment 2 employed a subset of the stimuli for Experiment 1, specifically a subset of the mid-band and high-band noises that were recorded in the two most reverberant rooms (Room 10 and Room RR). As in Experiment 1, ILDs in the recordings were digitally removed at the outset, and ITDs were limited to ±60 μs.

Mid-band tests were conducted at three different levels of coherence: Coherence=0.45 (using recordings with coherence=0.4 and 0.5); coherence=0.65 (using recordings with coherence=0.6 and 0.7); and coherence=1.0. Stimuli for coherence=1.0 were generated from randomly selected room recordings with the left KEMAR ear signal sent to both of the listener's ears. High-band tests were also done at three coherence levels: coherence=0.65, coherence=0.8, and coherence=1.0.

The goal of Experiment 2 was to measure a threshold ITD, as in Experiment 1, when there was an opposing ILD, i.e., to measure $\Delta t(\mathrm{ILD})$. The magnitude of the opposing ILD was fixed on each test run at one of three values: 0, 1, or 2 dB.

Unlike Experiment 1, which used a constant-stimulus method, Experiment 2 used a staircase procedure. Like Experiment 1, the task was two-interval forced-choice. The first interval always presented an original ILD-equalized recording, and the second interval presented the same recording modified by both an added ILD and an added ITD. The sign of the ITD was randomized from trial to trial, and the sign of the ILD always opposed the lateralization cue of the ITD. Both intervals were turned on and off with 200-ms raised-cosine envelopes.

The listener's task was to report whether the second stimulus was to the left or right of the first, and the value of Δt was increased or decreased across trials to find the threshold ITD for which the listener's responses were consistent with the ITD. The staircase was of the 3-down 1-up form (Levitt, 1971), and therefore, the method found an ITD threshold equivalent to the 79.4% consistent point on a psychometric function. Thus, in terms of method, Experiment 2 was the staircase analog of the constant-stimuli method used in Experiment 1; both found a threshold ITD.

The staircase search was terminated after eight turns, and the mean of the last six turns was used as the threshold ITD estimate for the run. A run was also terminated, and discarded, if the ITD exceeded 1000 μs. Runs typically took 5 to 10 min to complete. Each listener completed three runs for every combination of noise band coherence and opposing ILD.

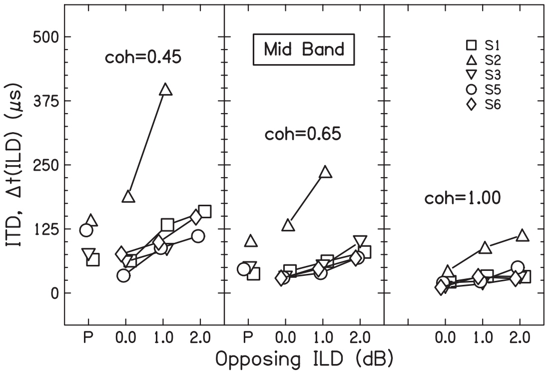

FIG. 6. Results of Experiment 2 for the mid-frequency noise band (715 Hz). Threshold values of interaural time difference are reported for each listener (individual plots), depending on the intensity of an opposing interaural level difference and on noise-band coherence (separate panels). Each connected symbol represents the mean for three staircase runs. Disconnected symbols at the left (p) are predictions from Experiment 1 for an opposing ILD of 0 dB. Symbols have been slightly jogged left and right for clarity.

B. The mid-band results

Figure 6 shows the results of Experiment 2 for the mid band. The connected symbols in each plot give the threshold ITD for a listener (mean of three runs), as a function of the magnitude of the opposing ILD (0, 1, or 2 dB). Results for the three different mid-band coherence conditions (coherence=0.45, 0.65, and 1.0) are given in separate panels of the figure. The individual plots within each panel show results for each of the five listeners.

An advantage of the ITD-threshold method used in Experiment 2 is that in the special case that ILD=0, the thresholds can be compared with predictions from the psychometric functions in Experiment 1, based on the 79%-consistent points. There were four listeners in common for those two experiments, and the predictions are shown by the disconnected symbols (P) on the left in Fig. 6. For a coherence of 0.65 the correspondence was good for all four listeners (correlation=0.98), and for a coherence of 0.45 it was good for three of the four.

Figure 6 shows that threshold ITD values measured for four of the five listeners (S1, S3, S5, and S6) were remarkably similar to one another.[1] Values for the fifth listener, S2 (plotted with the upward triangle symbol), were always higher than the others. S2 also participated in Experiment 1, and in that experiment his ITD thresholds were also the highest of the group. In Experiment 2, when the opposing ILD was 2 dB, it was impossible to measure a threshold for S2 whenever the coherence was less than 1.0, because the opposing ILD overwhelmed the ITD. All of these runs had to be terminated because the threshold search exceeded the maximum limit of 1000 μs.

A notable observation regarding the mid-band results is that with each increment in coherence (from 0.45 to 0.65 to 1.00) there was a marked change in the ITD vs. ILD functions. The change followed the same pattern for all listeners, including S2. As will be shown below, the perceptual weighting of ITD cues was lowest when coherence was lowest, and the weighting increased with each increase in coherence.

The nature of the ITD-threshold method in Experiment 2 is that the staircase converges on values of ITD that do not

TABLE I. Slopes of best-fitting lines showing the listeners' time-intensity tradeoffs in Experiment 2.

Stimulus	Listener(s)	Coherence	Slope (μs/dB)
Mid band (715 Hz)	S1, S3, S4, S6	0.45	40
		0.65	23
		1.00	9
	S2	0.45	209
		0.65	104
		1.00	35
High band (2285 Hz)	All listeners	0.65	353
		0.80	94
		1.00	45

directly give trading ratios, i.e., for a given ILD, the threshold value of ITD is not the trade-off value. However, if threshold ITDs are plotted as a function of ILDs, the slope of the plot *is* the trading ratio.

For each of the three coherence conditions, a line was fitted to the average results for listeners S1, S3, S5, S6, and a separate line was fitted to the individual results for listener S2. The slopes of those lines, reported in Table I, are estimates of the time-intensity tradeoff. For the four similar listeners, the tradeoff was 40 μs/dB, for a coherence of 0.45, approximately half that (23 μs/dB) when coherence increased to 0.65, and approximately half again (9 μs/dB) when coherence increased to 1.0. For listener S2, the slopes were much steeper, but they were ordered in the same way.

C. The high-band results

Results for the high-band are given in Fig. 7. As shown by the disconnected symbols, predicted values from Experiment 1, available for three listeners at a coherence of 0.65, agreed with the zero-ILD thresholds from Experiment 2, except for listener S2.[2] The threshold ITDs in Experiment 2 were again highest for the anomalous listener S2, but they were closer to those of the other four listeners. Therefore, data for the five listeners were analyzed as a single group for the high band. When listening to noise bands with a coherence of 0.65, all five listeners had perceptions of ITD that were fragile in the sense that an opposing ILD of even 1 dB greatly increased the ITD threshold, and an opposing ILD of 2 dB completely overwhelmed the ITD, leading to terminated runs and immeasurably large ITD thresholds. With a coherence of 0.8 on the other hand, ITD cues were given more substantial weight by all listeners making it possible to measure all thresholds. With a coherence of 1.0, ITD cues were given even more weight.

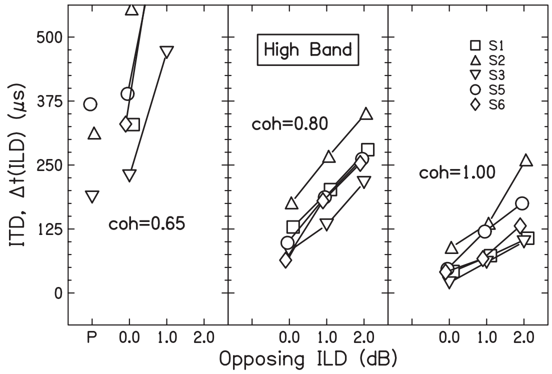

FIG. 7. Same as Fig. 6 except for the high-frequency noise band (2850 Hz).

For each value of coherence, lines were fitted to the threshold ITD functions, averaged over the five listeners, to estimate the time-intensity tradeoff. The slopes are reported in Table I. The pattern was similar to that seen with the mid band, with the ITD taking on increasing weight as coherence increased. At the lowest level of coherence tested (coherence=0.65) the slope was 353 μs/dB. At the highest (coherence=1.0) it was just 45 μs/dB, and for coherence =0.80, it was intermediate, 94 μs/dB.

D. Overall

Trading ratios measured in ITD-ILD competition experiments like Experiment 2 are notoriously varied. They range from 2 μs/dB to hundreds of μs/dB (Domnitz and Colburn, 1977). They depend upon the baseline values of ITD and ILD and upon the range of ITD and ILD in the experiments. They appear to depend upon the psychophysical method (Lang and Buchner, 2009). Free-field experiments by Macpherson and Middlebrooks (2002) suggest that when sounds are well externalized, ILDs are downweighted. Our experience with listener S2 shows that trading ratios are different for different listeners, as also noted by McFadden *et al.* (1973). Our opinion about trading-ratio experiments is that if the experimental conditions are well controlled, useful results may yet be obtained by comparing trading ratios for different stimuli.

The comparison of trading ratios in the high band and the mid band used the same listeners and the same experimental conditions, e.g., the same ILDs. Averaged over all listeners, trading ratios were greater for the high band than for the mid band. Although we are aware of only one previous measurement of the trading ratio in the high-frequency range (McFadden *et al.*, 1972), greater trading ratios would be expected for the high band because listeners are less sensitive to ITDs at high frequencies (Henning, 1974, 1980; Bernstein and Trahiotis, 1982).

Comparing Experiment 2 with Experiment 1 affords an opportunity to test for scaling between the trading ratio and sensitivity to ITD. If it is assumed that both trading and sensitivity depend on a sense of lateral position cued by ITD, and if it is further assumed that the lateral position cued by ILD is independent of frequency range (Yost, 1981), then one expects scaling to hold. For a coherence of 0.65, the mean trading ratio from Experiment 2 (Table I including listener S2) is greater for the high band by a factor of 9. For a coherence of 0.6 (close to 0.65) the mean ITD threshold from Experiment 1 (Figs. 2 and 3) is greater for the high band by a factor of 7 (close to 9). However, for a coherence of 0.65 (average of 0.6 and 0.7) that high-band/mid-band ratio is reduced to a factor of 4. At the highest values of coherence tested, the mean trading ratio from Experiment 2 (Table I, coherence=1.0) is greater for the high band by a factor of 3. The ITD values for comparable high performance

(90%–99% consistent) from Experiment 1 (Figs. 2 and 3, coherence=0.8) are greater for the high band also by a factor of 3. In conclusion, some scaling does seem to hold, approximately.

The trading observed in Experiment 2 gives a new perspective on the thresholds from Experiment 1. Although Experiment 1 found that useful ITD cues were available with a mid-band coherence of 0.4 or a high-band coherence of 0.7, Experiment 2 suggests that these values of coherence may be so low that the ITD may be largely discounted in the computation of location in favor of other cues such as the ILD. In the end, the hypothesis that motivated this experiment was supported. The ILD-ITD tradeoffs favor the ILD as the coherence decreases.

Shinn-Cunningham *et al.* (2005) made acoustical measurements using a KEMAR manikin in a room indicating that the ITD was actually less degraded by room reflections than the ILD. Based on those physical measurements alone, one might predict that in normal listening conditions in a room, ITD cues would be weighted more strongly than ILD cues. This prediction would be contrary to the spirit of our conclusion in Experiment 2. There are, however, several points to be made about this difference in spirit. First, the experiments by Shinn-Cunningham *et al.* were broad band (200–3000 Hz), which favors sharp cross-correlation functions and well-preserved ITDs. For instance, Hartmann *et al.* (2005) found that with a very wide band, KEMAR recordings showed excellent preservation of accurate ITDs, monotonic with azimuth, even for distant sources in a reverberation room. By contrast, Experiments 1 and 2 used narrow bands. Second, using ITDs to localize successfully requires more than accurate ITD preservation. As shown by Experiment 1, localization by ITD is badly degraded if the coherence is not high. Coherence values measured by Shinn-Cunningham *et al.* were low (less than 0.5) for large azimuths, even though the source was always within 1 m of the manikin.

Finally, it should be noted that Experiment 2 does not prove an advantage for ILD for normal listening in a room. Experiment 2 treated ITD and ILD asymmetrically–the coherence, affecting ITD perception, was subjected to room effects, the ILD was not.

E. Application to hearing aids

One potential benefit of hearing aids is an enhanced ability to localize sounds, especially following a period of acclimation to the aids (Byrne and Dirks, 1996). Improved localization in the horizontal plane can occur following a bilateral fitting (Noble and Byrne, 1990) or a unilateral hearing aid fitting (Noble and Byrne, 1991), depending on the type and degree of hearing loss and upon the audiometric configuration (Byrne and Noble, 1998).

In his textbook on hearing aids, Dillon (2001) pointed to the audibility of low-frequency signal components ($f < 1500$ Hz) as particularly important for horizontal localization. That emphasis was partly based on experiments showing the greater importance of low-frequency ITD cues compared to ILD cues as measured in free field (e.g., Sandel *et al.*, 1955; Wightman and Kistler, 1992). However, Experiment 2 shows that the weighting of ITD and ILD cues is not fixed. Rather, it depends importantly upon the level of binaural coherence, with the ITD becoming increasingly discounted as coherence declines.

Experiment 2 suggests that when localizing sounds in a room, where coherence is reduced, a hearing aid user is likely to rely less on ITD cues and more on ILDs. It is therefore notable that the use of ILD cues can be complicated by hearing aids, especially if the aids employ amplitude compression (Musa-Shufani *et al.*, 2006). Use of directional microphones can also lead to ILD distortions and biased localization (Keidser, *et al.*, 2006; Van den Bogaert *et al.*, 2006).

Listeners who frequently adjust the gains of individual hearing aids for maximum comfort produce a variable distortion of the ILDs. Such listeners may then find themselves continuously reprogramming their auditory space maps. Because ILDs appear to be especially important for localization in rooms, there could be an advantage to yoking the gains of left and right hearing aids in everyday conditions.

IV. EXPERIMENT 3: LOW BAND

Experiment 3 measured ITD sensitivity for a low band (center frequency=225 Hz). The goal of the low-band experiment was to clarify the role of coherence in localization when the waveform ITD is a useful cue. The mid-band results from Experiment 1 showed that ITD sensitivity depends on waveform coherence, independent of other acoustical characteristics of the room. One might extend that observation to hypothesize that so long as the frequency is low enough for waveform ITDs to be useful cues, the ITD sensitivity is determined by the value of the coherence alone.

An immediate implication of this coherence-alone hypothesis is that keen ITD sensitivity leading to excellent localization should occur at low frequencies because coherence is always high at low frequencies. As shown by Fig. 1, the binaural coherence of a noise band tends toward 1.0 as the band center frequency tends toward zero because the wavelengths become so long that the noises at the two ears necessarily resemble one another (Lindevald and Benade, 1986). Consequently, the coherence is high, even in a reverberant environment.[3]

An alternative to the coherence-alone hypothesis begins with the idea that coherence in rooms at low frequency should not be described as "high," but should be described as "physically compressed." Coherence plots like Fig. 1 for different rooms show that low-frequency coherence values actually do become smaller in increasingly reflective environments, but they do not become much smaller. For instance, the smallest value ever measured in any room in the 225-Hz band by Hartmann *et al.* (2005) was 0.75. Accordingly, an alternative hypothesis says that sensitivity to ITD depends strongly on very small, but consistent changes in coherence when the frequency is low.

In Experiment 3, listeners were tested with two sets of KEMAR recordings in the 225-Hz band, one set with perfect coherence (coherence=1.0), the other with coherence=0.85.

Maximal ITD sensitivity was expected for the perfect coherence condition. The coherence-alone hypothesis predicts that ITD sensitivity in Experiment 3 for a coherence of 0.85 should be similar to ITD sensitivity in Experiment 1 for a coherence of 0.8. The alternative hypothesis makes no such prediction.

A. Methods

Five listeners participated in the experiment. Two of them (S4 and S5) had previously participated in Experiment 1. The other listeners (S7, S8, S9) were new. The new listeners were all male. They ranged in age from 21 to 25, and all of them had normal hearing.

The stimuli for the experiment were rectangular noise bands, one-third octave wide and centered on 225 Hz (edge frequencies were 200 Hz and 250 Hz). Three such noises were recorded via KEMAR in Room 10 at a distance of 3 m. Each recording was made at a different and arbitrary location in the room. All three recordings had measured coherence values very close to 0.85 (0.83 to 0.87), and the ITDs were close to zero (±60 μs). Any level differences present in these recordings were digitally removed. A second set of stimuli with perfect coherence was then derived from these recordings by duplicating one ear signal in the opposite channel.

Testing for the low band followed the same procedures as for the mid-band test of Experiment 1, including use of the same ITDs ($\Delta t=25$, 75, 125, and 175 μs). The two low-band stimulus sets (coherence=0.85 and coherence=1.0) were presented to listeners in separate test runs, with the order of these runs randomly interspersed. For each condition, a listener completed a total of 5 runs of 48 trials each, resulting in a total of 60 judgments per ITD value. For comparison, listeners S4 and S5 had completed a test with the mid band at coherence=0.80 as part of Experiment 1. The three new listeners completed runs for the mid-band as part of the present experiment (two runs of 40 trials each, 20 judgments per ITD value.) These runs were randomly interspersed with their low-band runs.

B. Results and discussion

The results of Experiment 3 are given in Fig. 8. Figure 8(a) compares mean performance for the two low-band conditions: coherence=0.85 and coherence=1.0. As expected, sensitivity to the ITD was high when coherence was perfect. The psychometric function for coherence=1.0 rose steeply and exceeded 95%-consistent for all values of $\Delta t \geq 75$ μs. The function for coherence=0.85 rose much more gradually and remained well below 95%-consistent even at the longest ITD tested (84%-consistent for $\Delta t=175$ μs).

Threshold estimates based on 75%-consistent scores were 35 μs for coherence=1.0 and three times that, or 115 μs, for coherence=0.85. A statistical comparison found that the listeners scored significantly higher for the coherence=1.0 condition at every ITD tested (Bonferoni-protected paired t-tests, $p<0.05$ in all cases). Clearly the small reduction in low-band coherence from 1.0 to 0.85 sharply reduced listeners' sensitivity to the ITD.

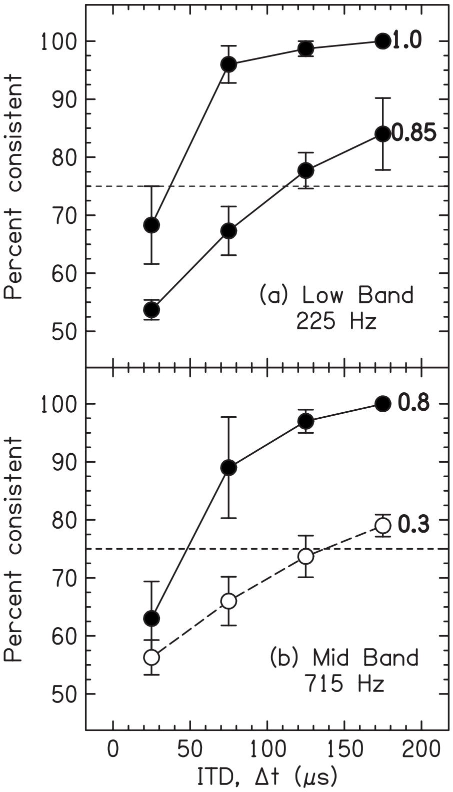

FIG. 8. (a) Same as Fig. 2, but for the low band used in Experiment 3. There were two values of coherence as indicated. (b) Mid-band results to compare with part (a).

The solid-line function in Fig. 8(b) shows the performance of these same listeners for the *mid-band* stimulus with coherence=0.80. That performance resembles the performance for the *low-band* stimulus with coherence=1.0, and a statistical comparison found no significant difference in performance for these two conditions at any ITD ($p>0.05$ in all cases).

The most telling result of Experiment 3 compares ITD sensitivity in the low band for coherence=0.85 with the ITD sensitivity in the mid band at the very similar coherence value, coherence=0.80. The threshold estimate for the mid-band condition was 45 μs, less than half the threshold for the low band at coherence=0.85. A listener-by-listener comparison was made for each ITD, and in 18 of 20 cases (5 listeners × 4 ITDs) the listener's mid-band score exceeded the corresponding low-band score.

Experiment 1 found that equal levels of coherence for a band led to very different interaural-time sensitivity, depending on whether the frequencies were low enough to support waveform ITD sensitivity. Experiment 3 clearly shows that performance is again very different for the mid band and the low band, both of which provide waveform ITD cues. To estimate the extent of this difference, a visual comparison was made between the low-band function for coherence =0.85 and the whole family of coherence functions for the mid band shown in Fig. 2. The closest match was to the mid-band function for coherence=0.3, which is reproduced in Fig. 8(b) (dashed line plot). Center frequencies of the mid band and the low band differed by just over a factor of three (715 Hz/225 Hz=3.2). These equivalent coherence values differed by just under a factor of three (0.85/0.3=2.8). It is reasonable to suppose that some form of scaling holds good on the low-frequency decreasing edge of the coherence function, as it appears in Fig. 1, but we cannot prove that this kind of scaling should hold. Whether or not scaling holds, it is evident that the coherence-alone hypothesis fails. Sensitivity to ITD depends on both the coherence and the center frequency of the noise band.

V. SUMMARY AND CONCLUSIONS

Interaural time difference (ITD) cues are important to the localization of sound sources. When the stimulus is a noise, those cues are chiefly conveyed by the steady-state portion of a signal (Tobias and Schubert, 1959; Giguère and Abel, 1993). Devore *et al.* (2009) have regarded this fact as indicating that listeners employ a suboptimal neural processing strategy. The present study investigated listeners' sensitivity to steady-state ITD cues in narrow-band noises that were recorded in rooms, where the binaural coherence of signals was reduced by room reflections. The narrow bands were either below 1300 Hz (mid band at 715 Hz and low band at 225 Hz) or above 1300 Hz (high band at 2850 Hz). With the mid band and low band, listeners can detect ITDs in the signal fine structure. With the high band, they can detect ITDs only in the signal envelope (McFadden and Pasanen, 1978; Henning, 1980).

Experiment 1 measured listeners' sensitivity to ITDs in mid-band noises or high-band noises with seven different values of coherence ranging from 0.2 to 0.8. Experiment 3 measured sensitivity in the low band. Experiment 2 measured the perceptual weight of ITDs when an opposing interaural level difference was present in the stimulus. The key variables in Experiment 2 were, again, the frequency range of a noise band (mid band vs. high band) and the coherence. Results of the experiments supported the following conclusions:

1. When listening to mid-band noises with a coherence as low as 0.2, listeners were able to gain some crude information about ITDs. Physical measurements of binaural coherence in rooms (Hartmann *et al.*, 2005) indicate that 0.1–0.2 is about the lowest coherence ever seen in rooms.
2. Listeners' sensitivity to ITDs in mid-band noises increased monotonically with increasing coherence over the full range of coherence values tested here (0.2 to 0.8).
3. The sensitivity to mid-band ITD shows reliable perceptual changes with changing binaural coherence when baseline coherence values are between 0.2 and 0.5. This is an interesting result because it differs from JND experiments that depend on the perception of binaural diffuseness or apparent source width. The diffuseness experiments show that listeners can detect very small changes in binaural coherence when the baseline coherence is 1.0 (e.g., Gabriel and Colburn, 1981; Goupell and Hartmann, 2006), but the just-detectable changes are large for other baseline values. For instance, Gabriel and Colburn (1981) found that for a baseline coherence of zero, coherence JNDs ranged from 0.3 to 0.7, depending on the bandwidth. Pollack and Trittipoe (1959) measured coherence JNDs as the baseline coherence increased from 0.0 and found that as the baseline coherence increased to 0.5, the JNDs only decreased from 0.5 to 0.3 approximately.[4]

   In contrast to the diffuseness experiments, the psychometric functions of our Experiment 1 show that changes in coherence as small as 0.1 reliably alter a listener's ability to gain location information from the ITD in the low-coherence range 0.2 to 0.5. Similarly, Jeffress *et al.* (1962) found prominent changes in the effect of ITDs as the coherence varied from 0 to 0.3. Therefore, it appears that ITD sensitivity is uniquely capable of revealing significant perceptual effects when the coherence is low.

   The distinction between diffuseness and ITD-sensitivity may find a physiological correlate in the different stages of binaural processing. Working with unanesthetized rabbits, Coffey *et al.* (2006) found that at the sub-cortical level, JNDs in coherence were often almost constant across all values of reference coherence, including the very low coherences which revealed consistent changes in ITD sensitivity in our Experiment 1. By contrast, at the cortical level, most units showed a rapidly accelerated change to coherence near a coherence of 1.0, similar to the perception of diffuseness. A similar progression along the ascending pathway had been previously observed in barn owl by Albeck and Konishi (1995).
4. Experiments with the high band showed that coherence levels had to be as least twice as high as required for the mid band in order to achieve comparable sensitivity to steady-state ITD cues. This very likely reflects the fact that at high frequencies listeners have access to ITD cues in the signal envelope only. Room surfaces are usually somewhat more sound absorbing at higher frequencies than at lower frequencies, which tends to cause binaural coherence to increase with signal frequency in a room. However, listeners may gain little localization advantage from this increased coherence because *much* higher levels of coherence are required to detect ITDs at high frequencies.

   The above comparison between high and mid bands is definitive in connection with the ITD-mediated localization of noise in rooms. It is not definitive with regard to high-frequency capabilities of the auditory system, as shown by the envelope modulation experiments by Bernstein and Trahiotis (2002, 2003, 2007).
5. Differences among rooms, particularly differences in reverberation time, were found to be an unimportant factor in ITD sensitivity. Instead, the determining factor was coherence. In a given frequency range, ITD sensitivity was approximately the same function of coherence in all rooms tested.

   There are alternatives to coherence. Working with specially tailored envelopes, Bernstein and Trahiotis (2009) tried to decide whether (1) the cross-correlation at zero lag or (2) the height (coherence) and width of the peak in the cross-correlation function was better able to predict ITD sensitivity for high-frequency stimuli. They concluded that neither model successfully accounted for their threshold ITDs. In the present experiments the envelopes were established by interference among the components in the band, leading to a systematic statistical relationship between these two measures. Therefore, our experiments are unlikely to be able to distinguish between these two cross-correlation models.

(6) Experiment 3 showed that although the coherence may be high in a low-frequency band, the ITD sensitivity may not be keen. A comparison with Experiment 2 showed that comparable ITD sensitivity occurred in the mid band (715 Hz) and the low band (225 Hz) when coherence in the mid band was much smaller. This result might have been expected. At low frequencies where the wavelength of sound is much greater than the head diameter, the interaural phase difference (IPDs) is small, and the variation in IPD across the frequency components of a noise band is also small. Consequently, coherence tends to be large. By contrast, sound localization is mediated more by ITDs than by IPDs (Zhang and Hartmann, 2006). Small variations in IPD lead to large variations in ITD at low frequencies because the ITD is equal to the IPD divided by the angular frequency. Presumably it is the large variations in ITD across the components of a band that lead to ambiguous sound localization and the observed ITD insensitivity at low frequencies when the coherence is only a little less than 1.0.

(7) Measurements of time-intensity trading in Experiment 2 found a direct relationship between the binaural coherence and the perceptual weight of ITD cues. This suggests that when localizing noise in rooms, where coherence can be well below unity, listeners will discount steady-state ITD information in favor of other available cues to source location.

(8) A comparison of ITD sensitivity across the three one-third-octave bands in our experiments shows that maximum sensitivity occurs for the mid band. Thus, ITD sensitivity is a non-monotonic function of frequency. It is interesting to ask which band is the most sensitive. We have inadequate data to answer this question, but we can make conjectures. The most sensitive band will surely be well below 1300 Hz because waveform ITDs are completely inaccessible above 1300 Hz (Zwislocki and Feldman, 1956), but how far below? Hartmann *et al.* (2005) argued that the region near 500 Hz ought to be particularly important. For a human head in an isotropic field, the cross-correlation function shows a minimum near that frequency (Lindevald and Benade, 1986). Therefore, when a listener experiences a sound with even a moderate value of coherence in this frequency region (e.g., 0.4) it is likely to result from direct sound with useful information about location. It makes sense for the binaural system to develop the means to cope with small coherences in this frequency range. Our measurements of cross-correlation functions in different rooms regularly show minima between 700 and 900 Hz (Fig. 1 is an example.) Perhaps, our mid band, centered on 715 Hz, is about optimal.

A limitation of the experiments in this article is that the essential independent variable, namely the coherence, was measured over the duration of the entire stimulus, a full second. Alternatively, listeners may use a series of short-term binaural analysis intervals (Shinn-Cunningham and Kawakyu, 2003). Our analysis of short-term correlations (Fig. 5) showed that the range of mean short-term coherences was compressed for small coherence. By contrast, the ITD psychometric functions in Experiment 1 (Fig. 2) decreased substantially with decreasing coherence in the range of small coherence. The clear monotonic relationship between the psychometric functions and long-term coherence tends to support the long-term coherence as a useful predictor of localization.

A second limitation on the generality of the experiments in this article is that they were essentially headphone experiments. The experimentally added ITDs were the same for every component in the band. Similarly, in Experiment 2 where ILDs were introduced, the added ILDs were uniform among all components. Only the ITDs and ILDs intrinsic to the original binaural recordings were responsible for the incoherence in the stimuli. Unlike a two-interval sound localization experiment in which sources are located at different positions in a room, the coherence was the same on the two intervals of our experiments. So were the envelopes in the left and right ear stimuli. Because the binaural recordings were made with a manikin and not with a listener's own ears, different listeners probably experienced different degrees of externalization.

Nevertheless, the ITD reweighting as a function of coherence as reported in this article is strongly suggestive of an effect that can be expected in a room. It remains for future experiments to establish a clearer relationship between interaural parameters and noise localization in diverse real room conditions.

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[1] The one exception was that listener S3's runs had to be terminated for all tests with a coherence of 0.45 and an opposing ILD of 2 dB. In this respect only, listener S3 performed more like listener S2 and less like listeners S1, S5, and S6.

[2] Reliable threshold predictions were not available for the other two listeners because the psychometric functions in Experiment 1 did not cross the 79%-consistent line.

[3] Hartmann and Aaronson (2008) showed that if ITDs are normally distributed with standard deviation σ, then the ensemble average coherence is given by $\exp(-\omega_o^2\sigma^2/2)$, where ω_o is the center frequency of the band. This function tends to 1.0 at low frequency.

[4] Axis labels in the articles by Pollack and Trittipoe are given as the square of the coherence. As noted by Jeffress and Robinson (1962), these labels should actually be the coherence itself. Consequently, in viewing the plots in those articles the reader should simply ignore the exponent 2 in the axis labels.

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