Lateralization of sine tones–interaural time vs phase (L)

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Listeners estimated the lateral positions of 50 sine tones with interaural phase differences ranging from −150° to +150° and with different frequencies, all in the range where signal fine structure supports lateralization. The estimates indicated that listeners lateralize sine tones on the basis of interaural time differences and not interaural phase differences. [DOI: 10.1121/1.2372456]

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I. INTRODUCTION

Since the time of Lord Rayleigh (Strutt, 1907) it has been known that human listeners can localize or lateralize tones on the basis of interaural phase differences (IPDs) or interaural time differences (ITDs). For a tone of given frequency there is a simple relationship between the two interaural parameters, IPD$=360° f$(ITD), where IPD is measured in degrees. Thus IPD and ITD are almost the same thing, but there is a proportionality factor which is the frequency of the tone, f.

The distinction between IPD and ITD causes one to wonder if one of these two measures of interaural difference correlates better with the human perception of sidedness. *A priori*, the IPD has a built-in advantage in that there is a fixed physical terminus for the measure. As the phase increases to 180°, the IPD of a sine tone loses its significance whatever the ITD or the frequency. Further, measurements of just noticeable deviations from the midline show that the JND in IPD is roughly independent of frequency, whereas the JND in ITD is not (Yost and Hafter, 1987).

On the other hand, the azimuth of free-field sources correlates better with ITD because, for a given azimuth, the ITD changes little as the frequency varies while the IPD changes a lot (Kuhn, 1979). If human listeners gain their internal measures of laterality from experience with the physical positions of audible objects, then the ITD would have a natural advantage.

Auditory models following the Jeffress model (Jeffress, 1948) tend to emphasize the ITD because fixed internal delay lines that compensate externally imposed ITDs lead to a topographic encoding based on ITD. However, this encoding is confined to frequency-specific channels. Within any tuned channel, the ITD is approximately equivalent to an IPD. Consequently, it is not possible to argue that the ITD enjoys a clear advantage based on neural architecture. On the contrary, the distribution of IPD-sensitive neurons across frequency, as observed in the inferior colliculus of guinea pig (McAlpine *et al.*, 2001) suggests that IPD may be more fundamental physiologically, because the neural population seems to be distributed according to IPD.

On the other hand, cross-frequency models used to study human lateralization of broad-band stimuli are based on a common ITD in different frequency channels (Stern *et al.*, 1988). The "straightness" criterion for ITD is a frequency-independent ITD and not a frequency-independent IPD. To the extent that straightness is perceptually important, the ITD has the edge.

In 1981, Yost performed a series of experiments on the lateral position of sine tones as a function of interaural phase difference. In separate IPD experiments, he measured the perceived location of tones with frequencies between 200 and 1500 Hz. In these experiments, the interaural phase varied from −150° to +180°. Listeners were required to indicate the position of the tone image on a scale from left to right.

Yost found that the overall aspect of the laterality-vs-IPD curves seemed to be independent of frequency. By contrast, the lateralization responses were different functions of ITD for different frequencies. Consequently, the experiments suggested that the human binaural system was acting more as an IPD meter than as an ITD meter.

A potential problem with Yost's experiments is that trials were blocked on frequency. Therefore, if listeners use the full range of available responses for each experimental block, then experiments in which the range of IPD is the same in each block would lead to the conclusion that laterality is the same function of IPD whatever the frequency of the tone. Yost was aware of this possibility and performed spot checks with pairs of tone frequencies to test his results. The checks supported the dominant position of the IPD, but those checks fell short of a full experiment.

Recent measurements of Huggins pitch laterality (Zhang and Hartmann, 2004) caused us to become aware of context sensitivity for lateralization judgements made by listeners. A similar informal observation had been made for tones by Sayers (1964). To pursue these observations, we performed an experiment on sine-tone laterality using IPD as the principal variable, as in the experiments done by Yost. The difference was that trials were not blocked on frequency.

II. EXPERIMENT

The experiment used two fixed sets of 25 sine tones with parameters selected to be in ranges where tones can be lateralized on the basis of ITDs or IPDs in the fine structure (Zwislocki and Feldman, 1956; Yost and Hafter, 1987). The

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TABLE I. Interaural Parameters—Stimulus Set 1.

Stim. No.	ITD (μs)	IPD (°)	Freq. (Hz)
1	−200	−30	417
2	+400	+30	208
3	−600	−30	139
4	+800	+30	104
5	−200	−60	833
6	+400	+60	417
7	−600	−60	278
8	+800	+60	208
9	−1000	−60	167
10	+200	+90	1250
11	−400	−90	625
12	+600	+90	417
13	−800	−90	313
14	+1000	+90	250
15	−400	−120	833
16	+600	+120	556
17	−800	−120	417
18	+1000	+120	333
19	−400	−150	1042
20	+600	+150	694
21	−800	−150	521
22	+1000	+150	417
23	0	0	167
24	0	0	333
25	0	0	694

intention was to cover the entire range of IPD, frequency, and ITD where discrimination is good while remaining mainly within that range. Such "reasonable" parameters were selected as follows: First, the IPDs were 0°, ±30°, ±60°, ±90°, ±120°, and ±150°, the same as those used by Yost, except for 180°. Here, a positive sign means that the fine structure leads on the right. Second, the ITDs were well distributed, never greater than 1000 μs, and normally less than the low-frequency head-diffraction physiological range of 763 μs. Third, the frequencies resulting from the IPDs and ITDs were in the range from 100 to 1250 Hz and were normally less than 1000 HZ.

A. Stimuli

The ITDs, IPDs, and frequencies of Stimulus Set 1 are shown in Table I. Stimulus Set 2 was identical except that plus and minus signs in the table were reversed. Consequently, the experiment was left-right symmetrical overall.

The tones were calculated by an array processor and were stored in buffers with a length of 32,768 words per channel. The buffer contents were converted to analog signals by two 16 bit digital-to-analog converters at a sample rate of 20 ksps. Hence, the total stimulus duration was 1.6 s. The onsets and offsets were smoothed by raised-cosine functions 100 ms in duration. The phase delay for the signal for one ear was applied to the waveform fine structure only, not to the raised-cosine envelope. Converted signals were low-pass filtered at 2.5 kHz with Brickwall filters with a slope of −115 dB/octave. Digital recordings made at the output of the filters verified the waveform phase shifts and envelopes. The listener heard the stimuli through Sennheiser HD 414 headphones while seated in a double-walled sound-treated room. The level of the tones was 60 dB sound pressure level.

B. Listeners

Five listeners participated in the experiment: A (age 19), C (65), W (66), X (31), and Z (33). Listeners were male except for C. Listeners all had normal hearing, defined as thresholds within 15 dB of nominal, throughout the frequency range of this experiment. They were all experienced in binaural listening tasks and were right handed. Listeners X and W were the authors.

C. Procedure

The listening tests were organized as runs of 25 trials. Each run employed the 25 stimuli of Set 1 or Set 2, presented in random order. Runs with Set 1 and runs with Set 2 alternated.

On each trial, a listener heard one of the tones from the stimulus set. The listener could repeat the tone as many times as desired. Then the listener responded with a number between −40 and +40 to indicate the lateral position of the image of the tone. Except for A, listeners had extensive experience in lateralizing tones on the −40 to +40 scale in connection with another experiment. There was no feedback. A typical run lasted 3–5 min, depending on the listener. Final data were based on the last ten runs for a given listener.

D. Results

The first step in analyzing the data was to determine an average response, for each listener, to each of the 44 different stimuli with nonzero IPD and to each of the six stimuli with zero IPD. Occasionally, a tone with a positive or negative IPD led to a response with the opposite sign (opposite side of the head). In order to avoid unwarranted cancellation of positive and negative responses in finding the mean, it was necessary to perform some filtering on the data. Responses to stimuli with IPD greater than or equal to 90° were excluded if the responses had a sign opposite to the IPD. All other data were included. Out of 440 data points for each listener, 20 were excluded for listener A, 27 for C, 55 for W, 23 for X, and 22 for Z.

Next, the included responses for stimuli having a particular IPD were collected and averaged. The standard deviation was also found. These values of mean and standard deviation are shown in Fig. 1. Similarly, means and standard deviations for stimuli having particular ITD values were found, and those are shown in Fig. 2.

1. Standard deviations

If the sensation of lateral position is a function of IPD, the standard deviations, shown as error bars in Fig. 1, should be small. To test this idea, standard deviations for individual listeners were computed in the following way: First, the mean response was calculated for each of the 50 stimuli. Next, a mean and variance were calculated for each IPD value based on the means for individual stimuli, using as a weighting factor the number of included responses for each

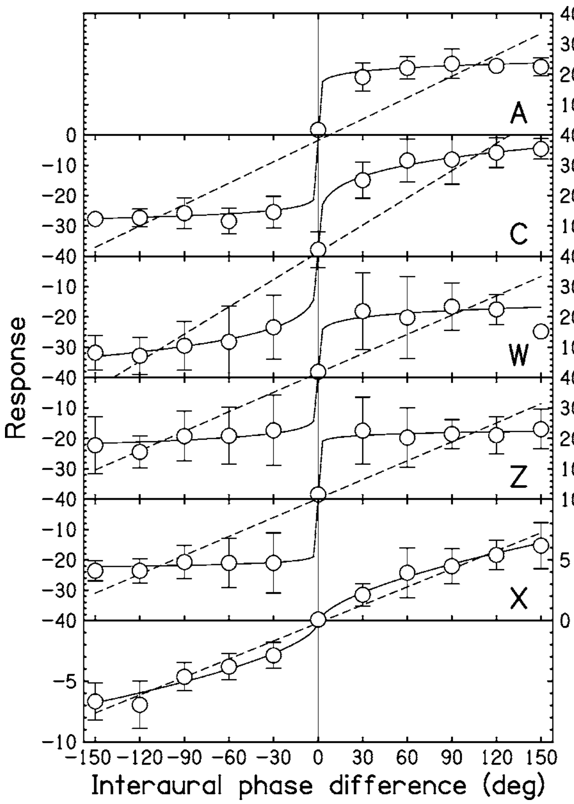

FIG. 1. Lateral position responses for five listeners plotted as a function of interaural phase difference (IPD). Each symbol shows the mean response to four or five tones with a given IPD. Error bars are two standard deviations in overall length. Dashed lines show the best linear fits. Solid lines show the best nonlinear fits.

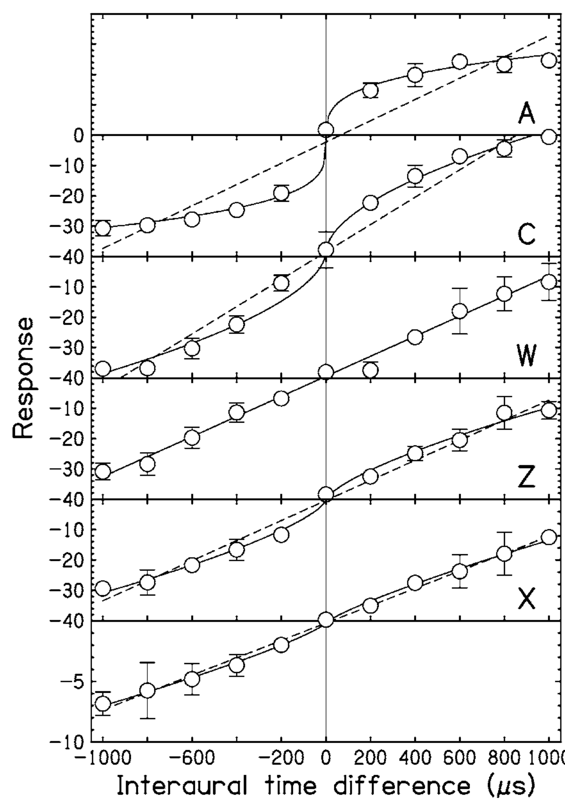

FIG. 2. Same as Fig. 1, but plotted against interaural time difference (ITD). Where no error bars are shown the standard deviation is smaller than the data points.

stimulus. The square roots of the variances are the standard deviations in Fig. 1. The standard deviations averaged over the ten finite IPD values are reported in Table II. Similarly, standard deviations were computed from the same raw data regarded as functions of ITD, and averaged over the ten finite ITD values.

Table II shows that the standard deviations are smaller when responses are regarded as a function of ITD, not of IPD. Such a result argues in favor of ITD as the effective interaural parameter. A two-sample *t*-test, based on ten means for finite IPD and ten means for finite ITD, showed that the standard deviations are significantly smaller for ITD than for IPD for all five listeners, with *p*-values shown in Table II.

An alternative calculation of the variances simply averaged the raw responses for each IPD (or ITD). The means were the same as in the figures, but the standard deviations were sufficiently larger that the distinction between IPD and ITD was significant at the 0.01 level only for listeners C, W, and Z. Although standard deviations were smaller for ITD than for IPD for the other two listeners as well, the difference was not significant. The disadvantage of this later computation is that it incorporates all the variation on individual trials.

2. Restricted range of IPD

When the absolute value of the IPD is 90° or less, one expects that lateralization judgments are only little affected by alias images outside the region of centrality. Therefore, we performed a new test excluding all the data with IPDs greater than 90°, but with no other filtering. The test was otherwise identical to that of Sec. II D 1 above. The test showed that the standard errors were significantly smaller for ITD than for IPD, with $p < 0.001$ for all listeners except for listener A. For A, $p < 0.02$.

3. Straight-line fits

If the perceived lateral position is an accurate IPD meter, then the responses in Fig. 1 above should be a linear function of IPD. Straight lines were fitted to the data by minimizing the rms error. Similarly straight lines were fitted to the ITD data in Fig. 2. The fitting procedure simply fitted all included responses for all values of IPD or ITD.

The rms error was smaller for the ITD straight line than for the IPD straight line for all five listeners. Averaged over

TABLE II. Standard deviation for each listener averaged over ten mean responses to tones with nonzero IPD or ITD. The *p*-values less than 0.05 support the hypothesis that the standard deviations for ITD are less than those for IPD.

Listener	IPD	ITD	*p*-value
A	3.7	2.2	0.01
C	7.3	2.2	$\ll 0.01$
W	8.5	3.9	< 0.01
Z	6.9	2.9	$\ll 0.01$
X	1.4	1.1	0.05

TABLE III. Best-fit parameters for the nonlinear model and rms error, E.

Listener	$L=a(\mathrm{IPD})^q+b$				$L=a(\mathrm{ITD})^q+b$			
	a	b	q	E	a	b	q	E
A	18.1	−1.9	0.07	4.1	4.12	−2.0	0.28	2.8
C	12.6	1.4	0.20	7.6	0.84	1.5	0.56	3.7
W	13.6	0.8	0.10	9.3	0.03	0.5	1.00	4.5
Z	18.3	0.1	0.04	7.0	0.24	−0.3	0.70	3.5
X	0.3	−0.2	0.60	1.4	0.02	−0.2	0.82	1.2

listeners, the error for ITD was less than half the error for IPD, indicating that lateral position is better represented as a linear ITD meter than as a linear IPD meter. However, neither representation is good because lateral position is clearly a nonlinear function of the interaural parameters for most listeners. The linear fits are shown by dashed lines in Figs. 1 and 2.

4. Nonlinear fits

A reasonable fit to the lateral position data can be obtained with a function of three parameters: constant bias, scale factor, and exponent. Exponents less than 1.0 indicate compression. Such nonlinear functions were fitted to the data as functions of IPD and of ITD to minimize rms error. The final parameters and rms error are shown in Table III. The table shows that the rms errors are always smaller for the ITD functions, suggesting that lateral position is a better monotonic function of ITD than of IPD. The nonlinear fits are shown by solid lines in Figs. 1 and 2.

For listeners A, W, and Z, the exponents are close to zero ($q \leqslant 0.1$) for the IPD fits, corresponding to constant values of the model responses independent of IPD except for the sign. Therefore, for these three listeners it can be said that the lateralization responses are essentially not functions of IPD.

5. Individual differences

The plots in Figs. 1 and 2 show that the five listeners were rather different in several important respects. Whereas most of the listeners lateralized the stimuli over a large range of azimuths and gave responses over the allowed range from −40 to +40, listener X lateralized all the stimuli close to the midline. Listeners exhibited different amount of compression. But despite such individual differences, all listeners appeared to base their lateralization judgements on ITD and not on IPD.

III. CONCLUSION

Five listeners estimated the lateral positions of 50 sine tones with interaural phase differences of 0°, ±30°, ±60°, ±90°, ±120°, and ±150°. The interaural time differences ranged from −1000 to +1000 μs, and the frequencies were all in the range where lateralization can be based on signal fine structure.

The lateralization estimates were evaluated as functions of IPD and of ITD. The evaluations revealed that the estimates were well described as functions of ITD and not as functions of IPD. Evaluations included standard deviations of estimates for given interaural parameters as well as goodness of fits for simple linear and nonlinear functions. The conclusion that human listeners lateralize tones based on ITD and not on IPD agrees with results by Schiano *et al.* (1986)–limited to ITDs smaller than ours–but is at variance with other previous research (Sayers, 1964; Yost, 1981). It appears that these previous experiments were biased by blocking experimental trials with respect to frequency. It seems likely that listeners learn their sine-tone localization scales from objects in the real world, which leads to a scale based on ITD. However, the extreme limits of the scale are established by the IPD, as is logically necessary. The dominant role of the ITD no longer holds when the IPD exceeds an extreme value, somewhere in the vicinity of 180°. The results support a direct application of cross-correlation models, such as the Jeffress model, to human sound localization.

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