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BINAURAL LATERALIZATION AND SUBJECTIVE LATERAL POSITION  
SPACE

City University of New York

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BINAURAL LATERALIZATION  
AND  
SUBJECTIVE LATERAL POSITION SPACE

by

Huan-yuan Tzuo

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This manuscript has been read and accepted for the Graduate Faculty in Psychology in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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BINAURAL LATERALIZATION  
AND  
SUBJECTIVE LATERAL POSITION SPACE

by

Huan-yuan Tzuo

Adviser: Professor Eli Osman

ABSTRACT

This dissertation determined subjective lateral position judgements (accurate to  $\pm 0.12$  degrees) of images for low-frequency binaural tones with various interaural phase (time) shifts.

A paradigm with a standard interval followed by a signal interval was used. The binaural signal was a 250-Hz tone of 50-msec total duration with 10-msec rise/fall times, set to 70 dB SPL. The monaural standard was presented 0.5 seconds before but was otherwise identical to the binaural signal. Three standard conditions were employed: silent interval (no standard), left ear standard, right ear standard. Sixteen interaural phase differences ( $\theta$ s) were selected, covering a wide range ( $\pm 105^\circ$ ). For each  $\theta$ , four local values ( $\theta_{1s}$ ) spaced  $2^\circ$  apart and centered at  $\theta$  were

randomly presented trial by trial. Ultimately, for each  $\theta$ , four distributions of subjective position judgements for the four  $\theta_i$  values,  $P(\theta_i)$ , were determined, and were collapsed into one  $P(\theta)$  distribution. Statistical properties for each  $P(\theta)$  distribution were computed, including the mean  $\bar{P}$ , the standard deviation  $\sigma_P$ , skewness, and a test for normality. The process was repeated for each value of  $\theta$ .

Without standard, mean  $\bar{P} \approx \theta/2$  for  $|\theta| \leq 105^\circ$ . With the monaural standard,  $\bar{P}(\theta)$  is shifted away from the ear that received the standard. Statistics of  $P$  depend on  $\bar{P}$ , not  $\theta$ .  $\sigma_P$  increases as  $\bar{P}$  moves laterally from midline and ranges from (midline values) near  $3^\circ$  to about  $15^\circ$  (around  $45^\circ$  off midline). Near midline  $P$  distributions appear skewed laterally. Near either ear they appear skewed towards the midline.

Without standard, the global  $\bar{P}(\theta)$  slope is less than any local slope for  $\bar{P}(\theta_i)$ . The  $\bar{P}(\theta)$  and  $\sigma_P(\theta)$  results for no standard yield an excellent quantitative fit to results on interaural phase difference discrimination. The standard effect cannot be explained by either adaptation or an 'effective' interaural amplitude shift. It weakens the theoretical relationship, implied by previous models, between the structure of the peripheral binaural system and the scale of subjective position.

This study provides quantitative results that appear to be a reliable and valid representation of the statistical properties

of lateralization space, and should be important for further understanding of binaural hearing.

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## TABLE OF CONTENTS

	Page
ABSTRACT	iv
ACKNOWLEDGEMENTS	vii
TABLE OF CONTENTS	viii
LIST OF TABLES	x
LIST OF FIGURES	xi
CHAPTER	
I.    INTRODUCTION	1
A.    Auditory Localization	
B.    Auditory Lateralization	
C.    Interaural Time and Intensity Discrimination: JNDs	
D.    Time-Intensity Trading	
E.    Models of Binaural Interaction	
1.    Count-Comparison Models	
2.    Cross-Correlation Models	
3.    Lateralization Models	
4.    Position-Variable Model	
II.   METHODS	86
A.    Subjects	
B.    Apparatus	
C.    Procedure	
1.    Experimental Design	

2. Psychophysical Methods	
3. Data Analysis	
III. RESULTS	111
IV. ADDITIONAL CONTROLAL CONSIDERATIONS	159
V. DISCUSSION	177
APPENDIX	227
BIBLIOGRAPHY	237

## LIST OF TABLES

Table	Page
1. Sample Results of the Measurement of the Linearity of the Pointer Position and the A-D Digital-Output.	94
2. Measurement of Subjects' Mechanical Variability.	110
3. Correlation between the Four Actual Values of Phase Shift and Their Computer-Output Data for Variations in Nominal Interaural Phase Difference.	112
4. Means and Standard Deviations of Lateral Image Position Distributions for Variations in Interaural Phase Difference and the Condition without Standard.	113
5. Means and Standard Deviations of Lateral Image Position Distributions for Variations in Interaural Phase Difference and the Condition with Left Standard.	115
6. Means and Standard Deviations of Lateral Image Position Distributions for Variations in Interaural Phase Difference and the Condition with Right Standard.	116
7. Averages of Means and Standard Deviations of Lateral Image Position Distributions for Variations in Interaural Phase Difference and All Three Conditions of Standards.	149
8. Means and Standard Deviations for the First One-Third and the Last One-Third of Trials for Sample Blocks of Data.	164
9. Standard Deviations of Lateral Image Position Distributions in Four Selected Interaural Phase Differences without Standard for the Control Study.	168
10. Means and Standard Deviations of Pressure Sensation Locus Distributions for Variations in Tack Position.	173
11. Means and Standard Deviations Averaged over Two Directions for Variations in Absolute Interaural Phase Difference and the Condition without Standard.	182
12. Slopes of the Regression Lines for the Sets of Four Actual Phase Shifts for Variations in Interaural Phase Differences.	189

13.	Averaged Local Slopes over Two Listeners and Two Directions Left and Right for Variations in Absolute Interaural Phase Difference.	190
14.	Chi-Squares and Measures of Skewness of Lateral Image Position Distributions for Variations in Interaural Phase Difference and the Condition without Standard.	193
15.	Chi-Squares and Measures of Skewness of Lateral Image Position Distributions for Variations in Interaural Phase Difference and the Condition with Left Standard.	195
16.	Chi-Squares and Measures of Skewness of Lateral Image Position Distributions for Variations in Interaural Phase Difference and the Condition with Right Standard.	196
17.	Means and Measures of Skewness of Image Position Distributions for All Stimulus Conditions and Listener HT.	197
18.	Means and Measures of Skewness of Image Position Distributions for All Stimulus Conditions and Listener PT.	198
19.	Predicted Interaural Phase JND's for Variations in Absolute Interaural Phase Difference.	205

## LIST OF FIGURES

Figure	Page
1. Path Length Difference between the Two Ears for a Distant Source at an Azimuth 0.	7
2. Interaural Time Delay $\tau$ for Tones and Clicks as a Function of Azimuth 0.	11
3. Interaural Intensity Difference Measured at the Two Ears as a Function of the Position of the Sound Source.	14
4. Angle JND for Tone Bursts as a Function of the Tone Frequency and the Angle between the Sound Source and the Median Plane.	32
5. Interaural Time Difference JND and Interaural Amplitude Ratio JND for Tone Bursts as a Function of the Tone Frequency.	36
6. Block Diagram of Cross-Correlation Model	49
7. Neural Network Proposed by Jeffress for Localization of Low-Frequency Tones.	55
8. Vector Diagram Illustrating the Addition of Out-Of-Phase Tones to In-Phase Narrow-Band Noise.	59
9. Block Diagram of the Position-Variable Model.	67
10. Block Diagram of the Model for the Peripheral Auditory System.	70
11. Block Diagram for a Possible Realization for the 'Binaural Displayer'.	76
12. Block Diagram of Apparatus.	88
13. Drawing of the Mechanical Device Used by the Listener for Communicating Lateral Image Position Judgements.	92
14. Sample of Four Individual Histograms of Subjective Position-Judgements for Four Actual Interaural Phase Shifts.	103

15.	Sample of the Histogram of Subjective Position-Judgements for the Combined Data of Figure 14.	105
16.	Sample of Working Sheet for Data Analysis.	107
17.	Mean Lateral Image Position as a Function of Interaural Phase Difference for Subject HT and the Condition without Standard.	118
18.	Mean Lateral Image Position as a Function of Interaural Phase Difference for Subject PT and the Condition without Standard.	120
19.	Mean Lateral Image Position as a Function of Interaural Phase Difference for Subject HT and the Condition with Left Standard.	122
20.	Mean Lateral Image Position as a Function of Interaural Phase Difference for Subject PT and the Condition with Left Standard.	124
21.	Mean Lateral Image Position as a Function of Interaural Phase Difference for Subject HT and the Condition with Right Standard.	126
22.	Mean Lateral Image Position as a Function of Interaural Phase Difference for Subject PT and the Condition with Right Standard.	128
23.	Standard Deviation as a Function of Mean Lateral Image Position for Subject and All Three Conditions of Standard.	134
24.	Standard Deviation as a Function of Mean Lateral Image Position for Subject and All Three Conditions of Standard.	136
25.	Standard Deviation as a Function of Mean Lateral Image Position for Subject HT. Data Points Are Replotted from Figure 23 by Collapsing across Three Conditions of Standard	138
26.	Standard Deviation as a Function of Mean Lateral Image Position for Subject PT. Data Points Are Replotted from Figure 24 by Collapsing across Three Conditions of Standard	140
27.	Standard Deviation as a Function of Mean Lateral Image Position for the Condition without Standard and Two Subjects.	142

28.	Standard Deviation as a Function of Mean Lateral Image Position for the Condition with Left Standard and Two Subjects.	144
29.	Standard Deviation as a Function of Mean Lateral Image Position for the Condition with Right Standard and Two Subjects.	146
30.	Mean Lateral Image Position as a Function of Interaural Phase Difference for Averages of Two Subjects and the Condition without Standard.	151
31.	Mean Lateral Image Position as a Function of Interaural Phase Difference for Averages of Two Subjects and the Condition with Left Standard.	153
32.	Mean Lateral Image Position as a Function of Interaural Phase Difference for Averages of Two Subject and the Condition with Right Standard	155
33.	Standard Deviation as a Function of Mean Lateral Image Position for Averages of Two Subjects and All Three Conditions of Standard.	157
34.	Drawing of Mechanical Pointer Device (Part of Figure 13).	167
35.	Standard Deviation as a Function of Interaural Phase Difference for the Control Study.	170
36.	Mean Position (Averaged over the Directions Left and Right) as a Function of Absolute Value of Interaural Phase Difference for the Condition without Standard.	184
37.	Measure of Skewness as a Function of Mean Lateral Image Position	200
38.	Comparison of Interaural Phase Difference JND between the Predicted Values in This Study and the Study by Yost.	207
39.	Standard Deviation as a Function of Absolute Mean Lateral Image Position for the Condition without Standard.	209
40.	Comparison of Lateralization Data between This Study for No Standard and the Study by Domnitz and Colburn.	215
41.	Comparison of Lateralization Data between This Study for Monaural Standard and the Study by Domnitz and Colburn.	217

42. Comparison of Standard Deviation of Lateral Image Position Judgements between This Study for no Standard and the Study by Stern and Colburn. 220

## I. INTRODUCTION

The existence of two ears is a very important and basic property of our auditory system. A person with normal hearing usually does not realize the advantage of having two good ears. With binaural hearing, people can easily and faithfully localize the sources of sounds and also concentrate on one source to the exclusion of others (this is the so-called 'cocktail party effect'). For the person who loses hearing in one ear, both the ability to locate a sound source in auditory space and the ability to detect a certain sound in a background of interference are severely degraded. Studies of the properties of spatial sensitivity in audition and signal detection in an acoustic environment are extremely important in psychoacoustics.

The primary basis of binaural hearing is the perception of differences between the stimuli presented to the two ears, which are referred to as interaural differences. Generally, for a sound source in a natural environment, the interaural differences are specified by comparison of the stimuli reaching the two ears. They result from differences in the signal propagation paths to the two ears and also the differential effects at the two ears of the listener's body, head, pinna, and other objects in the environment. In terms of binaural analysis, these interaural differences are usually described as interaural intensity differences and interaural time differences. For example, given

a tonal signal with fixed frequency, the interaural intensity difference can be described in terms of the ratio of amplitudes of the two stimuli at the two ears. The amplitude ratio can be replaced by the power, intensity, or energy ratio. The interaural time difference or time delay can be specified by the interaural phase difference of the stimuli at the two ears.

The term auditory localization refers to the perception of the direction and distance (i.e., spatial attributes) of a sound source in a natural environment. The basic information necessary to locate a sound source in the natural auditory space is obtained from the interaural differences at the two ears. The perceived location of a sound source is also influenced by the momentary orientation of the listener's head, visual information, and the listener's expectation of where the source is located. Normally, variations in these cues due to head motion contribute significantly to the localization process. Exactly how the different informational components are combined depends on the special situation in which the listener is operating.

Most studies of the processes concerned in auditory localization are not done in a natural environment, but rather in a controlled laboratory setting with artificial stimuli. Experimentally, the binaural stimuli associated with the interaural differences can be generated and precisely controlled to eliminate the effects of other related factors such as room echoes. One of the most common methods is to place the listener

in a sound proof chamber and present the stimuli through earphones, so that the interaural differences of the stimuli can be manipulated independently and precisely using electronic devices. While headphones are worn, the image of the sound source is located inside (or near) the head. The locus of the image, usually called a lateralized image, depends on the stimulus configuration. Data obtained via earphones are generally more reliable than data obtained in naturalistic environments because fine stimulus manipulation can be achieved and a variety of contaminating variables can be avoided. The term auditory lateralization is used to describe the process of judging the position of the apparent lateral image obtained through earphones, and to distinguish it from auditory localization. In other words, lateralization may be considered as a laboratory version of localization, and one which provides a more efficient way to study binaural hearing.

To locate a sound source accurately is not the only important function of binaural hearing. Using two ears, a listener can selectively attend to one particular sound source in a complex acoustic environment and effectively exclude others. This ability is particularly important in an environment with noisy surroundings, or when there are several sound sources competing for a person's attention. In an echo-free natural environment, such as inside an anechoic chamber, stimuli can be presented through the use of a multiple-speaker configuration,

which provides an efficient method to study selective attention. But, again, most studies are carried out in the refined laboratory with artificial stimuli controlled electronically. For example, one can measure, experimentally, the amount of selectivity in terms of the relative amounts of binaural masking (in decibels) of signals masked by noise. This is termed binaural masking level differences (BMLDs) and has been extensively studied in recent years. Such studies provide a better understanding of binaural processing and are theoretically relevant to understanding the functions of the auditory system.

Auditory localization, auditory lateralization, the discrimination of interaural differences, and binaural masking level differences are the most important areas of research in binaural hearing. The major concern in this dissertation is the lateralization of binaural tonal signals and the properties of subjective lateral position space. A brief review of the relevant literature will be presented in the following sections. Some of the binaural models dealing with binaural interaction, which are related to this project, will also be briefly summarized. Material concerning binaural masking level differences, which is not directly relevant to this project, will not be discussed.

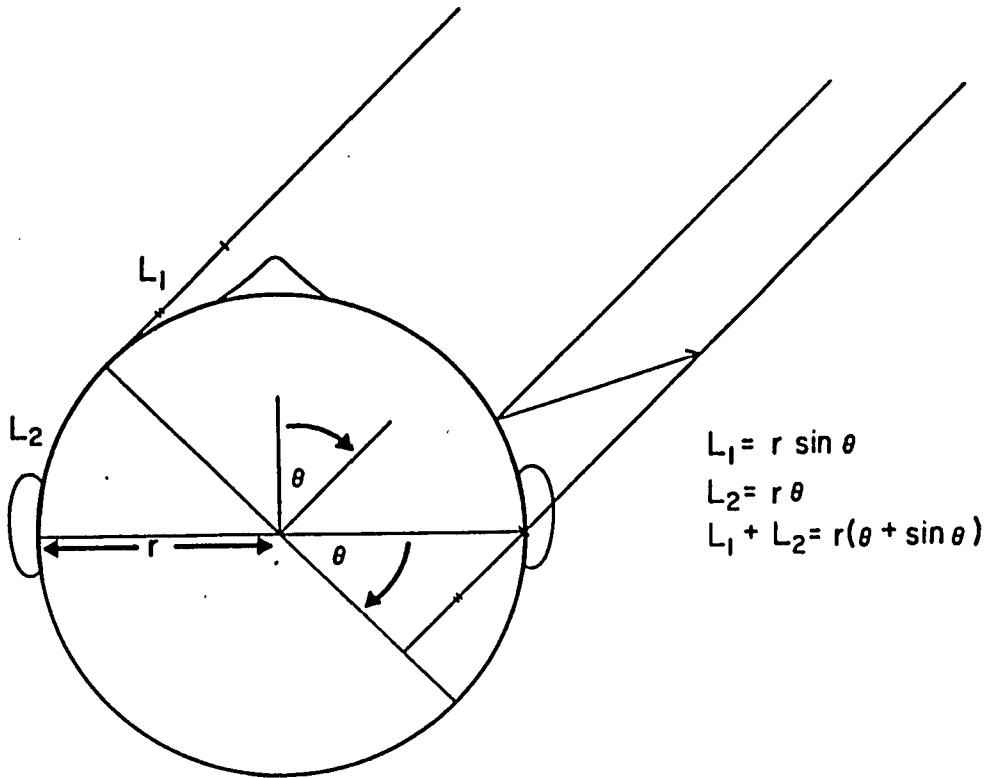
#### A. Auditory Localization

The cues used to localize a natural sound source depend on the nature of the source. The basic components of cues for

localization are provided by either interaural time differences or interaural intensity difference, or, for most cases, by the combination or interaction of these two different cues. Lord Rayleigh (1907) stated that low-frequency sinusoids are localized on the basis of interaural time differences, while high-frequency sinusoids are localized on the basis of interaural intensity differences. This is the so-called 'duplex theory' of sound localization. Most current investigations still support this theory.

Consider the following simple experiment. In an anechoic environment, a sustained pure tonal signal originates at one side of the head. Since the stimulus is generated without audible onsets or offsets, the listener can only use the information derived from the sustained tone to judge the location of the source. Physically, the sound reaching the farther ear will be delayed in time (phase delayed) and reduced in intensity (less amplitude) relative to the nearer ear. Referring to Figure 1, a diagram taken from Woodworth (1938), the interaural time difference between the signals arriving at the two ears for a given sound source can be computed approximately as follows. The head of the listener can be treated as a solid sphere and the two ears as point receivers located at opposite sides of the diameter of the sphere. The sound waves generated by a distant source, therefore, arrive at the two ears at different times because they traverse different pathways. An approximate

Figure 1. Path length difference ( $L_1 + L_2$ ) between the two ears for a distant source at an azimuth  $\theta$ . Reflections from the head will interact with the direct ray paths. One such interaction is illustrated on the right side of the drawing. (After Woodworth, 1938.)



computation of the difference in length of the two pathways can be given by

$$d = L_1 + L_2 = r(\theta + \sin\theta),$$

where  $r$  is the radius of the head (sphere) and  $\theta$  is in radians.

The average radius of the human head is assumed to be about 8.75 cm and the velocity of sound is about 344 m/sec. The difference in time, then, can be calculated by

$$\tau = (r/c) (\theta + \sin\theta) = 254(\theta + \sin\theta),$$

where  $c$  is the velocity of sound, and  $\tau$  is in microseconds.

Based on this formula, if a sound source is placed directly in front of the head, then  $\theta = 0$ , and  $\tau = 0$ ; thus, there is no time difference between the two ears. If the sound source is placed directly to the right (or left) side of the head, then  $\theta = \pi/2$ , and there is a maximum time difference of about 653  $\mu\text{sec}$ .

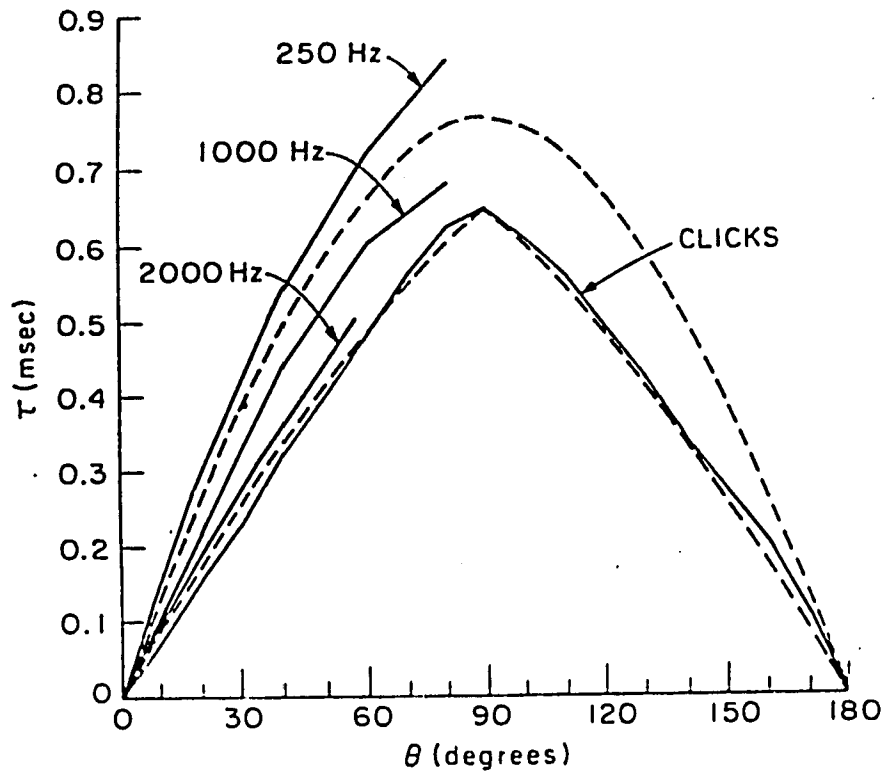
The above computation is just an approximation because the reflections of the sound from the head and interactions of these reflections with the waves proceeding directly to the two ears are not considered. One such interaction between the reflected wave and a directly arriving wave is illustrated in Figure 1. Interactions may provide either reinforcements or cancellations in the resultant pattern of the waveform and may create effective phase shifts. Thus, predictions using the above approximation will not be equally valid at all frequencies. However, for transient signals, such as clicks or tone bursts, which contain all frequency components, it is a remarkably good approximation

(see Figure 2).

Figure 2 summarizes how the interaural time delay,  $\tau$ , depends on the azimuth angle,  $\theta$ , for tones and clicks. Three sets of data for tonal signals were derived from interaural phase measurements made on artificial heads. The results are for 250 Hz, 1000 Hz, and 2000 Hz (Firestone, 1930; Mills, 1958; and Nordlund, 1962). They show that the time delay is not independent of frequency, but tends to increase as the frequency is lowered. This suggests that for low-frequency tones interaural time differences would play a more important role than for high-frequency tones. The data for clicks were obtained by using real listeners with microphones placed at the entrance to the ear channel (Feddersen, Sandel, Teas, and Jeffress, 1957). Two theoretical curves (dashed lines) are derived from the model mentioned previously. The lower curve is derived by using the formula  $\tau = (r/c) (\theta + \sin\theta)$ , which is based on simple geometric considerations (Woodworth, 1938). The upper curve is derived by using the formula  $\tau = (r/c) (3\sin\theta)$ , which is a limiting case of diffraction theory (Rayleigh, 1945). In both cases,  $r$  is the radius of the human head (assumed to be 8.75 cm on average) and  $c$  is the velocity of sound (assumed to be 344 m/sec). Note that, in Figure 2, the data obtained by using clicks are remarkably well fitted by the theoretical curve.

Besides the interaural time differences, which can be directly estimated by using the geometric argument, the

Figure 2. Interaural time delay  $\tau$  for tones and clicks as a function of azimuth  $\theta$ . Solid lines represent data and dashed lines represent theoretical results. The solid lines representing the results for tones were derived from the summary of phase measurements presented by Shaw (obtained by Firestone, 1930; Mills, 1958; and Nordlund, 1962). The click data were obtained by Feddersen et al. (1957). For a detailed explanation, see text. (From Shaw, 1974).



interaural intensity differences also play an important role for the determination of the location of a sound source. Generally, for a given distant sound source located at one side of the head, the sound reaching the farther ear will be less intense than that at the nearer ear. But the intensity difference depends heavily on the frequency of the sound. Low-frequency sounds, which have a longer wavelength compared with the size of the human head, will bend (diffract) very well around the head, almost without any 'sound shadow'. Thus, interaural intensity differences for low-frequency sounds are very small and can be neglected. However, sounds of very high-frequency have a very short wavelength compared to the size of the head and thus, there will be a noticeable sound shadow. The interaural intensity difference may be as large as 20 dB.

Again, consider the simplest cases, for distant sustained pure tones. Some empirical data collected at different frequencies by Feddersen, Sandel, Teas, and Jeffress (1957) are represented in Figure 3. Interaural intensity differences were measured at the two ears for different frequencies located at different directions around the head. For frequencies of about 200 Hz or lower, the wavelength is about ten-times longer than the width of the head and the position of the sound hardly affected the size of the interaural intensity difference. Thus, the listener could not use intensity difference as a cue to determine the location of the sound. For frequencies at about 6000 Hz,

Figure 3. Interaural intensity difference measured at the two ears as a function of the position of the sound source. For a detailed explanation, see text. (From Feddersen et al., 1957.)



however, the dependence of the interaural intensity difference on position was dramatic and the sound shadow produced a difference of about 20 dB when the sound source was placed at or near  $90^\circ$  to the side. The marked asymmetry in interaural intensity differences (see Figure 3) at the two ears for a sound placed at the front of the head as compared to one at the back of the head might be based on the existence of the pinnae.

For a steady sinusoidal sound, interaural time differences (or delays) are easier to understand when translated into the form of interaural phase differences. For very low-frequency sounds, where the wavelength is much longer than the width of the head, the ongoing interaural time/phase difference will be a very clear cue for localization. However, if the wavelength is comparable with or less than the distance between the two ears, ambiguities of phase differences will occur. Referring to Figure 1, the maximum path difference (when  $\theta = \pi/2$ ) between the two ears (about  $8.75\pi$  cm) yields a time delay of about 653  $\mu$ sec. If the frequency of the sound source is about 750 Hz, the wavelength of the sound will be equivalent to the double of the path length between the two ears (around the head). Suppose this sound is placed at one side of the head ( $90^\circ$  azimuth). Then the waveform, when reaching the two ears, will be about in opposite phase ( $180^\circ$  out of phase). The signal at one ear will be either one-half-cycle ahead or behind that at the other ear; it will be impossible to decide which is leading and which is lagging.

Generally, as the wavelength of the sound becomes much less than the path difference between the two ears, such ambiguity will gradually increase. Finally, when signal frequency reaches and exceeds 1500 Hz, for a periodic sound, interaural phase differences no longer provide useful cues to locate the sound.

By using an anechoic environment, Stevens and Newman (1936) studied the localization of actual sound sources, including sinusoidal signals of different frequency, as well as tone bursts with smooth onsets and offsets. The listeners were asked to locate the sound in a horizontal plane at  $15^{\circ}$  intervals. The error rates of localization were lower at either very low frequencies or very high frequencies, and had a maximum for mid-range frequencies with a peak at about 3000 Hz. The results have been confirmed by a more recent study (Sandel, Teas, Feddersen, and Jeffress, 1955) using an echo-free chamber. The error curves show that the listeners performed better at localization of very high and low frequencies and poorest in the mid-range of frequencies (about 1500-3000 Hz). A special arrangement of two loudspeakers was used, which caused the resultant combined tonal stimulus to be leading in phase but less intense at one ear relative to the other. The data showed that listeners tended to localize the sounds towards the side with the phase lead for lower frequencies and towards the side with high intensity for higher frequencies. Near 1500 Hz, it was very difficult for listeners to locate the sounds accurately. All these findings conform to the 'duplex

theory'. For sinusoidal stimuli, at low frequencies (below about 1500 Hz), temporal (or phase) delay information is the major cue allowing listeners to localize the sound source, while intensity differences are more important for high frequencies.

### B. Auditory Lateralization

As has been pointed out already, lateralization is a refined laboratory version of localization. When a sound source is presented in a natural way and located outside the body, the sound image is readily localized externally in space in the direction of the actual source. In other words, the image is externalized (located outside the head) and fused (spatially compact and unitary). When a binaural stimulus is presented through earphones, the image is usually perceived to be near or within the listener's head. However, when earphones are worn, the externalization of an image still can be achieved under certain conditions. It depends upon a complex interaction of many factors, and is difficult to predict (or even describe) with precision (Durlach and Colburn, 1978). For example, the externalization of an image can be increased by presenting dichotic signals that have natural spectral characteristics and natural interaural differences. Furthermore, the concept that the cause of an in-head image is directly related to the use of headphones can be disproved, since in-head images can be obtained by using a multiple-speaker configuration in an echo-free chamber

(e.g., Jeffress, 1957; Leakey, 1957; Toole, 1970).

Generally, if there are no interaural differences, either in intensity or in time, the lateral image will be well fused and located in the median plan. When interaural intensity differences are introduced, the image will move toward the ear which receives the more intense stimulus. When interaural time differences are provided, especially for a stimulus carrying low-frequency timing information, the image will move toward the ear which receives the leading stimulus. One interesting phenomenon, known as 'binaural beats', can be used to show the ability of the binaural system to process phase (time) differences. Suppose a low-frequency pure tone is presented to one ear and a tone with a slight difference in frequency to the other. This is mathematically equivalent to the tone having a time-varying interaural time or phase shift, since the interaural phase difference is simply:  $(2\pi f_1 t - 2\pi f_2 t)$ . Listeners, under this condition, will experience a lateral sound image moving back and forth across the median plane periodically, at a rate corresponding to the frequency difference between the stimuli at the two ears. It must be remembered that binaural beats are completely different from physical beats. Physical beats, or 'unaural beats', are generated by mixing, electronically or acoustically, two tones with a slight difference in frequency. The two frequencies will be alternately in-phase and out-of phase and the intensity of the combined tone will fluctuate at a rate depending on the

frequency difference of the two original tones. Binaural beats, on the other hand, are based on an interaction in the nervous system responsive to inputs from the two ears. Neural firings in the auditory nerve at each ear seem to occur at a particular phase of the presented waveform (Kiang, Watanabe, Thomas, and Clark, 1965; Rose, Brugge, Anderson, and Hind, 1967). Thus, at some common neural center, probably the superior olive (Hall, 1965), the patterns of neural firings from the two ears may interact in varying ways depending upon the particular phase relation of the stimuli at the two ears. Consequently, some kind of subjective fluctuations (neurally based) will be produced when tones with slightly different frequencies are presented to the two ears.

Uniaural beats can be achieved over the entire audible frequency range. However, binaural beats can be clearly observed only in the range below approximately 600 Hz, become progressively more difficult to hear as the frequency increases, and are extremely difficult to hear for frequencies above 1000 Hz (Licklider, Webster, and Hedlund, 1950). Binaural beats can be still observed when a large interaural intensity difference is introduced (Tobias, 1963) and even when the signal intensity at one ear is below threshold (Green, 1964).

The major difficulty in binaural lateralization experiments is how to select a proper set of responses which may ensure that the listener can report his lateral image judgements accurately. Since the basic subjective experiences in lateralization

experiments are the changes in image position, the set of responses chosen will be, mostly, focused on the 'centroid' of the image rather than its spatial properties. 'Pointer' techniques, known as 'image-location indicators' were widely used in previous studies, such as when the listener was asked: to indicate whether the lateral image is right or left of the center (Sayers and Cherry, 1957); to move a mechanical lever or to match a point on a visual scale with the lateral position of the image (Teas, 1962; Sayers, 1964; Hafter, Bourbon, Blocker, and Tucker, 1969); to match the lateral image position with the location of a tactual sensation on the head (Békésy, 1960); to match the lateralization of two different sound images (Whitworth and Jeffress, 1961); or to match the lateral image position with an acoustic pointer based on interaural time adjustment (Moushegian and Jeffress, 1959) or on interaural amplitude adjustment (Domnitz and Colburn, 1977). Nevertheless, investigators in this area must still search for more refined and reliable methods since the lateralization judgements are very difficult to make and their precision is not as good as that of localizing an external sound source in a free field.

The quantitative details of lateral image behavior and, especially, the statistical properties of lateral subjective image space are still not clearly understood. Previous studies on lateralization with the binaural stimuli having only interaural intensity differences were mostly qualitative.

Binaural stimuli with only an interaural intensity difference and otherwise identical will produce a lateral image located away from the center of the head towards the ear which receives the more intense stimulus. If the difference is sufficiently large, the image will be fully lateralized at one ear, as if it were produced by the stimulus at that ear alone. The degree of lateralization has been found to be directly related to the size of the interaural intensity difference and independent of the type of signal, and the size of the interaural intensity difference required for full lateralization was estimated to be about 10 dB. For example, at a given intensity difference, the images are lateralized to almost the same extent for clicks, for noise, and for pure tones with frequencies above 3000 Hz (Békésy, 1960). Full lateralization can be achieved for click trains with interaural differences of about 10 dB, and that is independent of the intensity level of the clicks (Békésy, 1959). The value for noise bursts is also 10 dB, and independent of the intensity level and duration of the signal (Pineiro and Tobin, 1969). On the other hand, full lateralization can be observed with interaural intensity differences much less than 10 dB for clicks (Flanagan, David, and Watson, 1964) and much greater than 10 dB for tones and clicks (Moushegian and Jeffress, 1959; Whitworth and Jeffress, 1961; Guttman, 1962; and Sayers, 1964). Note that, the detailed relationship between lateralization and the interaural intensity difference has

not been systematically studied. In addition, the details of fusion of the image while varying the interaural intensity difference have also not been fully understood. The image will be fused very well when it is either located at the center or fully lateralized at the two sides and it will be diffuse or spread out when the image is located at around midway between the center and one of the sides (ears) (Harris, 1960; Whitworth and Jeffress, 1961; Sayers, 1964; Sayers and Lynn, 1968).

Compared with interaural intensity differences, interaural time differences in lateralization have been studied much more extensively, because, not only do the periodic characteristics of the signals have more important effects on lateralization but interaural time differences, rather than interaural intensity differences, are fundamentally more important for understanding binaural interaction processes. Similar to auditory localization, interaural time differences can be considered as a useful cue in lateralization only for lower frequency stimuli. For frequencies higher than 1500 Hz, the lateralization process degenerates and the image position will remain at or near the center of the head no matter what magnitude of interaural delay is introduced.

In general, for a pure tone of low frequency, the image position for the binaural stimulus will change periodically with the interaural time delay. The interaural delay period is approximately equivalent (in msec.) to the real time period of

the tone. As the interaural time difference is increased gradually from 0, the lateral image will be first well fused and located at the center of the head and gradually will move toward the leading ear as the delay changes from 0 to one-half of the period; it will become diffuse and difficult to judge when the interaural delay passes about one-half-period; and finally it will be refused again and returned to the center from the lagging ear when the interaural delay moves through the region of one-half-period to full-period. Note that, as has been discussed before, when interaural delay is about one-half-period, the waveform, when reaching the two ears, will be antiphase ( $180^\circ$  out of phase, corresponding to a phase shift of  $\pi$  radians), and it will be almost impossible for listeners to decide which ear is leading and which ear is lagging.

It has been pointed out earlier, that if a sound source is placed directly to the one side of the head, there is a maximum time difference of about 700  $\mu\text{sec}$  (more precisely, for the average adult head, 653  $\mu\text{sec}$ ). Empirical evidence shows that if one-half-period of the tone is much longer than 700  $\mu\text{sec}$ , i.e., the frequency of the tone is much lower than 700 Hz, the sound image will be heard all the way to one side. Lateralization will be gradually more difficult when one-half-tonal-period is reduced from 700  $\mu\text{sec}$ , and will be almost impossible when less than 300  $\mu\text{sec}$  (i.e., when the frequency of the tone is much greater than 1500 Hz). This critical value, 700  $\mu\text{sec}$ , of interaural time delay

is usually referred to as the Hornbostel-Wertheimer constant (Hornbostel and Wertheimer, 1920; Bekesy, 1960). Note that the critical value of interaural time difference is equal to the period of a tone of 1500 Hz. For any tonal signals having frequencies above that critical frequency (i.e., 1500 Hz), the binaural system becomes insensitive to interaural time differences.

By asking the listener to assign a position to each binaural fused sound image with the aid of a visual scale (a linear scale with 21 positions), Sayers (1964) studied the lateralization of tonal signals as a function of interaural delay over a wide range of frequencies. At frequencies above about 1500 Hz (with no interaural amplitude difference), the extent of maximum image position shift diminishes rapidly with increasing frequency. For frequencies between 200 and 1200 Hz, the results for different listeners exhibited different magnitudes of maximum lateral image position for different frequencies, but suitable linear expansions of the judgement scales were found to compensate for such differences across listeners and frequencies. However, for one listener, no such scale adjustment was needed to compensate for the results obtained at different frequencies. That the results for individual listeners with different signal frequencies show such close similarity suggests that the lateral image position shifts as a function of interaural phase delay are identical for the various signals. This seems to contradict the argument that maximum lateralization tends to

decrease with increasing frequency even within the low frequency region; but an alternative explanation is that the listener adjusts his judgement scale to cover a convenient range. This was confirmed by additional experiments (different frequencies were interlaced within a single run), in which it was shown that the maximum lateralization tended to decrease with increasing frequency. In addition, two other important conclusions can be drawn from Figure 2 of Sayers' (1964) study. 1) Lateral image position changes as a function of interaural delay with either the right or the left ear leading in phase, and the bimodal nature of the judged image positions with large interaural phase delays reflects the ambiguities in lateralization in the vicinity of the antiphase point. 2) The variability of the position judgements seems to change with interaural phase delay, but no detailed examination was made of this phenomenon.

Essentially the same direct measurement procedure as used by Sayers was used for the lateralization of a 200-Hz tone by Yost (1973), except that the stimulus to be judged was a part of a 13 unit train of 100-msec tones (the first 5, without interaural differences, served for reference, and the next 8, presented with either an interaural time or interaural intensity difference, served as test stimuli). Yost's results are consistent with Sayers (1964). Yost's range values indicate considerable variability in lateral position judgements, especially as the image moves away from the center.

A related experiment has also been conducted (Sayers and Cherry, 1957) in which the listener was required to judge whether the image is to the left or right of the center (without exact determination of position) for a wide range of frequencies. The major measurement made in this study was the degree of binaural 'fusion' which was represented in the form of 'binaural coherence curves', as a function of interaural time delay. For frequencies below 1250 Hz, consistent and smooth binaural coherence curves can be obtained which are directly related to interaural time delay. For frequencies significantly greater than 1600 Hz, the binaural coherence curves diminish and most response points lie near the chance line. Furthermore, the mechanism of binaural fusion was also considered as a form of statistical operation based upon the brain's execution of the running cross-correlation of the two ear signals. (This will be discussed in another section.)

Lateralization studies for continuous broad-band noise have results similar to those for low-frequency tonal signals, but the listener's experience is not periodical as it is for tones. As the interaural time delay increases beyond the value (1 msec, roughly) at which images will be fully lateralized, the image remains at the leading ear, but begin to diffuse and lose its compactness, and, eventually, when the interaural time delay reaches 20 msec, the image will become maximally diffuse and fill the whole head. Most broad-band noise studies were conducted in discrimination and detection paradigms, such

as: the ability to discriminate interaural noise correlation (Pollack and Trittipoe, 1959a, 1959b); the ability to detect signals in noise as a function of the interaural time delay in the noise and the interaural correlation of the noise (Jeffress, Blodgett, and Deatherage, 1952, 1962; Robinson and Jeffress, 1963; Langford and Jeffress, 1964; Rabiner, Laurence, and Durlach, 1966; Dolan and Robinson, 1967; Wilbanks, 1971); and the ability to judge the sidedness of noise with an interaural time delay (Blodgett, Wilbanks, and Jeffress, 1956). Some of these studies will be discussed in the following section. In summary, it is clear that, for broad-band noise, the binaural coherence curves show performance to increase rapidly from the chance line to the near perfect performance region as interaural time delay increases from zero, remain there over a large range of interaural time delays, and then, slowly return to the chance line again, where it remains for further increases of interaural time delay. Furthermore, for a very narrow-band low-frequency noise, the binaural coherence curves are very similar to the periodic curve for a pure tone at the center frequency of the narrow-band.

The phenomena of lateralization of broad-band clicks are roughly similar to those for broad-band noise, except for the way in which fusion breaks down as interaural time delay is increased beyond approximately 1 msec. For interaural time delays equal to or near zero, only a single well-fused click

image will be perceived by the listener and the position of that image depends on the value of interaural time delay. When the interaural time delay gradually increases within the region from 0 to 1 msec, the image gradually becomes lateralized to the side of the leading ear. As the interaural time delay increases beyond the value of about 1 msec, the lateral image splits into two images, one on the leading-ear side followed by another on the lagging-ear side. The appearance of these distinct images remains stable in the region of interaural delay, roughly, of about 1 to 5 msec (Teas, 1962; Guttman, 1962; Babkoff and Sutton, 1966). For further increases of interaural time delay, the lateralization of these two images (located at the two sides) will increase slightly, and they will finally be located and fully lateralized at the two ears, and undergo no further changes with respect to interaural delay per se. The value of interaural time delay for which no further interaction will occur was estimated to be about 15 msec (Guttman, 1962), and this value is roughly comparable to the interaural-delay at which broad-band noise no longer provides the perception of sidedness. Thus, there seems to be a second critical time constant of interaural time delay, which reflects a limitation on interaural memory for lateralization (Durlach and Colburn, 1978).

Studies of the lateralization of interaural time differences for complex stimulus configurations have also been carried out

widely. Since they are not directly related to the study reported here, only some empirical data are briefly summarized. For multiple-tone complexes, a well-trained listener can judge a variety of images and trajectories as interaural time delays are varied. That is, listeners can lateralize each component of a source separately (Sayers and Cherry, 1957; Sayers, 1964; Toole and Sayers, 1965a). For periodic click trains, a sophisticated subject can determine the lateral image position by tracking the fundamental component (the main feature of click trains) as well as the harmonics of the pulse train (Sayers and Toole, 1964; Toole and Sayers, 1965a, 1965b). For speech, results on lateralization and the binaural coherence curves are similar to those of broad-band noise (Cherry and Taylor, 1954; Cherry and Sayers, 1956; Sayers and Cherry, 1957; Cherry, 1961).

Besides lateralization there are related discrimination studies of either interaural intensity differences or interaural time differences, and the joint effects of these latter two factors have led to the concept of time-intensity trading. Such work will be discussed in the following two sections.

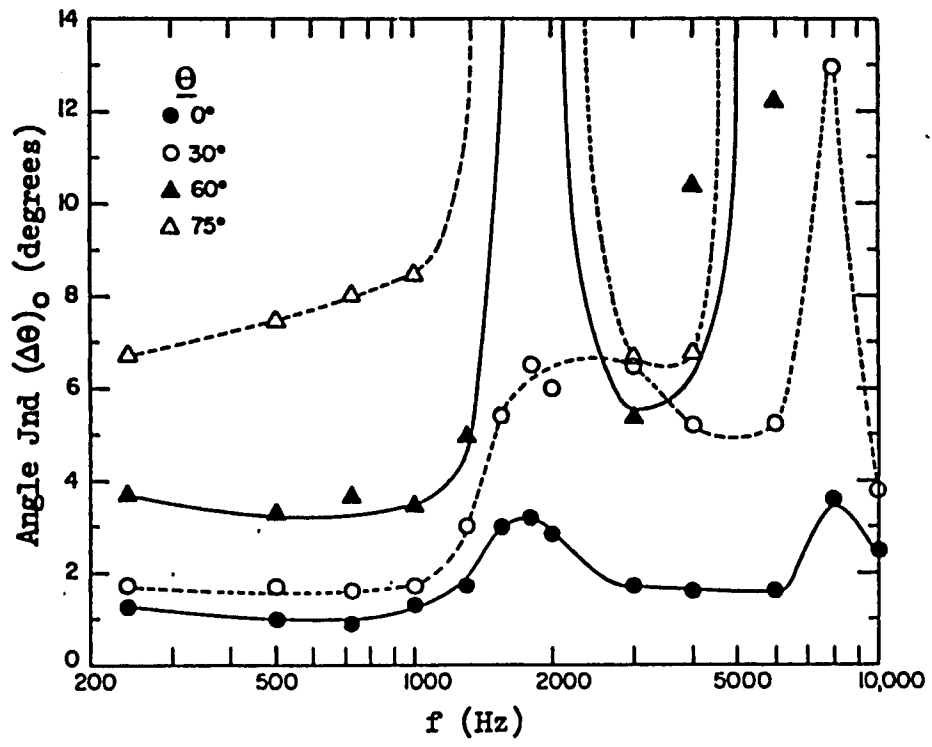
### C. Interaural Time and Intensity Discrimination: JNDs

In perception, especially in psychophysics, efforts are frequently made to determine the subject's sensitivity to differences among the various stimuli. The major component of binaural perception is perception derived from interaural

differences of binaural stimuli. In general, sensitivity can be measured in terms of thresholds or just noticeable differences (jnds) of stimuli (defined, as must be, with respect to some performance criterion or point of the psychometric function). Studies of interaural amplitude discrimination, interaural time discrimination, and their joint effects for either localization or lateralization have been extensively carried out. A brief summary of the empirical results follows.

First of all, a complete measurement of interaural discrimination for actual sound sources, successive pulses of tone, was made by Mills (1958). He measured (in an anechoic chamber with the listener's head constrained to prevent movement) the minimum directional displacement of the source that the listener could reliably detect as a function of the initial position of the source, and also as a function of frequency. (Mills' results are presented in Figure 4.) This is often referred to as the minimum audible angle in azimuth since it represents the minimum change in angular displacement of the source that is reliably detectable. The results show that the best position discrimination occurs when the source is placed straight in front of the listener ( $0^\circ$  azimuth). The minimum audible angle can be as small as  $1^\circ$ . It increases as the source moves away from the median plane and interacts strongly with tone frequency. With signals placed at more than  $45^\circ$  azimuth and frequencies from about 1500 Hz to 2000 Hz, the

Figure 4. Angle jnd  $(\Delta\theta)_0$  for tone bursts as a function of the tone frequency and the angle  $\theta$  between the sound source and the median plane. In those regions of  $\theta$  and  $f$  for which the curves exceed the maximum ordinate value of  $14^\circ$ , the jnd was found to be indeterminably large.  
(From Mills, 1972.)



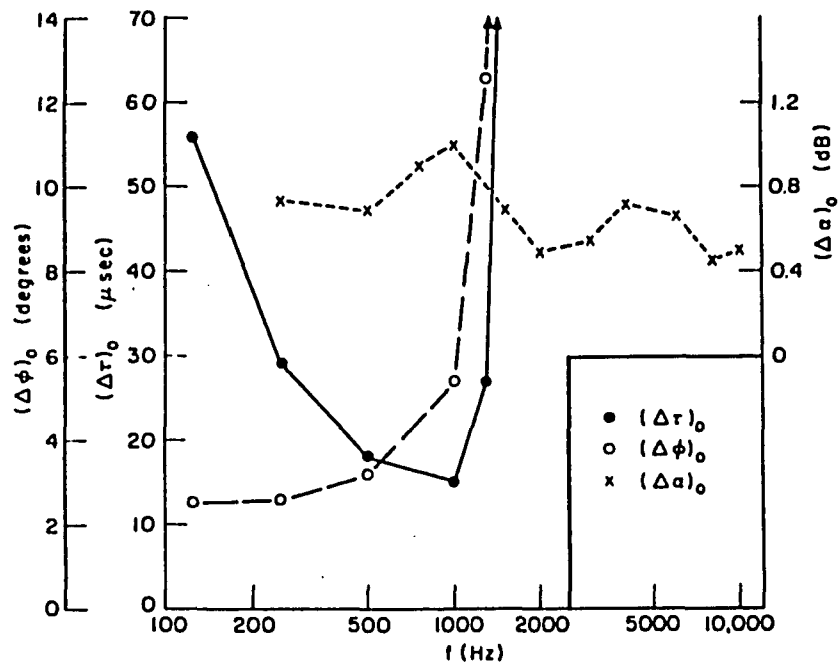
discrimination becomes extremely difficult. Minimum audible angles obtained by the method of adjustment have the same relation to frequency as those discussed above. Other investigators have employed different techniques to measure the minimum audible angle for actual sound sources and have obtained results that are in general agreement (Schmidt, von Gemert, De Vries, and Duyff, 1953).

When stimuli are presented through earphones, interaural discrimination is presumed to be based on judgements of the lateral image position produced by the interaural difference in time/phase or intensity or both. Zwislocki and Feldman (1956) measured the interaural phase difference that is just noticeable when equal-amplitude pulses of tone are presented with various phase delays at the two ears. The results show that jnds of phase difference (i.e., time delay) are as small as about  $2^{\circ}$  for tone pulses of frequency below 500 Hz. For frequencies over 1000 Hz, the binaural system is almost completely insensitive to interaural phase differences. Tobias and Zerlin (1959) found that the interaural time difference jnd for a burst of noise (low pass at 5000 Hz) is a function of the duration of the test burst. As duration is increased up to about 250 msec the function is close to linear such that the threshold decreases by about 2  $\mu$ sec for every doubling of duration. For bursts presented for more than about 700 msec, the thresholds remained at about 6  $\mu$ sec as duration was increased.

Mills (1960) measured interaural intensity discrimination (i.e., the interaural amplitude jnd), with co-phasic pulses of tone presented dichotically with various amplitude differences, as a function of the frequency of the tone. He found that the binaural system is more sensitive to interaural amplitude differences for high-frequency stimuli, as compared to low-frequency stimuli. He also compared the results obtained via earphones with results for actual sound sources, and found that the interaural difference jnd for intensity presented to the ears as a minimum audible change in the azimuth of an actual sound source is much smaller than the corresponding pure interaural intensity difference jnd for dichotic sources presented over earphones. At about 1500 Hz, these two functions converge on the same interaural difference in intensity, about 0.6 dB, and remain together through frequencies up to about 6000 Hz.

Figure 5 illustrates a summary representation of the interaural time difference jnd  $(\Delta\tau)_0$ , and interaural amplitude ratio jnd  $(\Delta\alpha)_0$  for a tone burst as a function of the tone frequency  $f$ . The interaural phase jnd  $(\Delta\phi)_0$  corresponding to  $(\Delta\tau)_0$  is also presented in the figure. The data for  $(\Delta\tau)_0$  and  $(\Delta\phi)_0$  are from Durlach's (1972) summary of the data of Klumpp and Eady (1956) and Zwislöcki and Feldman (1956); the data for  $(\Delta\alpha)_0$  are from Mills (1960). Some facts that can be drawn here are: (i) discrimination of interaural time, or equivalently,

Figure 5. Interaural time difference jnd  $(\Delta\tau)_0$  and interaural amplitude ratio jnd  $(\Delta\alpha)_0$  for tone bursts as a function of the tone frequency  $f$ . These data are for the zero interaural amplitude difference and zero interaural time difference reference conditions, respectively, and for tone bursts of roughly 1-sec duration and 50 dB SL. The interaural phase jnd  $(\Delta\phi)_0$  corresponding to  $(\Delta\tau)_0$  is also plotted. Discrimination of interaural time, or equivalently, interaural phase, was found to be impossible above roughly 1400 Hz. (From Durlach and Colburn, 1978.)



interaural phase, was found almost impossible above roughly 1400 Hz; (ii) the interaural time jnd,  $(\Delta\tau)_0$ , can be as small as a few microseconds, and is substantially smaller than any jnd for time resolution that has been obtained monaurally; (iii) the interaural time jnd,  $(\Delta\tau)_0$ , has a minimum at roughly 1000 Hz and becomes upwardly unbounded above approximately 1500 Hz; and (iv) binaural sensitivity to interaural amplitude difference shifts is roughly the same as monaural amplitude shift sensitivity.

Results on the effects of changes in interaural differences of time and intensity on discrimination performance are also available from more recent work (e.g., Hershowitz and Durlach, 1969; Domnitz, 1973; Yost, 1974; Domnitz and Colburn, 1977; and Ruotolo, Stern, and Colburn, 1979), and agree, at least in general, with the results discussed above. Some of those empirical data will be examined in detail in the Discussion Section, and consequently will not be described further here.

#### D. Time-Intensity Trading

Empirical evidence proves that interaural time and intensity differences are the two principal cues for localization as well as lateralization or image position judgement. By using earphones, it is possible to manipulate these two cues independently. Consequences of this fact are those experiments in which these cues can be placed in opposition; that is, the

stimulus arrives earlier at one ear while at the other ear it is more intense.

A lot of studies have used various combinations of the two interaural cues to study lateralization, and the results lead to the concept of trading between time and intensity. For a simple demonstration, if two low-pass filtered identical clicks are presented at the two ears via earphones, the image is usually located in the median plane. If the click at the right ear is adjusted to lead by a certain time relative to the left ear, the image will be shifted to the right of the center. However, by adjusting the click at the left ear to be more intense, it is possible to shift the image toward the left, and the image might move back to the center when the intensity difference at the two ears is adjusted to an appropriate magnitude, thus determining the trading ratio.

The value of the time-intensity trade has been measured in many studies by different methods with many different types of stimuli. The magnitude of the trading ratio is usually expressed in  $\mu\text{sec}/\text{dB}$ . It is clear that the result is affected by the various stimulus variables employed, such as intensity level, frequency or frequency band, duration of stimuli, presence of noise, etc. It is also affected by the method used to determine the ratio, as well as by intersubject differences. Thus, the measured values have been reported in a wide range, varying from  $1.7 \mu\text{sec}/\text{dB}$  for pure tones

(Shaxby and Gage, 1932) to 100  $\mu\text{sec}/\text{dB}$  for pulse trains (Christman and Victor, 1955), and to 300  $\mu\text{sec}/\text{dB}$  for low-pass filtered clicks with a high cutoff frequency (above 4000 Hz) (Harris, 1960).

Harris (1960) measured the trading ratio by using filtered clicks (high- or low-pass with various cut-off frequencies) to restrict the signal energy to a relatively narrow frequency region. Results indicated that the time-intensity trade depended on the frequency region of the transient signal. Low-pass clicks, with cut-off frequencies below 1500 Hz, gave values of about 25  $\mu\text{sec}/\text{dB}$ , whereas high-pass clicks gave values of about 90  $\mu\text{sec}/\text{dB}$ . Harris also found that when an image is centered by offsetting an intensity difference with a time difference, the variability of the judgement is greater than when stimuli equal in intensity are centered. Thus it seems that time differences and intensity differences may not be truly tradeable.

Studies by Whitworth and Jeffress (1961) and by Hafter and Jeffress (1968) suggested that both for tones of low frequency and for clicks, the listener could listen to either one of two perceptual images depending on the degree of training. For tones, the 'time image' was little affected by interaural intensity differences, and the trading ratio was about 1  $\mu\text{sec}/\text{dB}$ ; the 'intensity image' showed a value of about 20  $\mu\text{sec}/\text{dB}$  (Whitworth and Jeffress, 1961). For clicks, ratios for the 'time image' were reported to be from 2 to 35  $\mu\text{sec}/\text{dB}$ , and

ratios for the 'intensity image' were reported to be from 85 to 150  $\mu\text{sec/dB}$  (Hafters and Jeffress, 1968). In the study by Hafters and Carrier (1972), using a 100-msec 500-Hz tone burst, listeners were asked to discriminate a stimulus with opposing interaural difference settings (i.e., leading in time to one ear but more intense to the other) from a diotic signal (identical at the two ears). For a particular value of interaural time delay, the percentage of correct discriminations showed a minimum as the interaural intensity difference was varied. This indicated that a particular setting of the two parameters (in opposite directions) was the most difficult to discriminate from the diotic stimulus. This minimum, however, did not necessarily reach the chance line. Furthermore, as interaural time delay increased, the minimum was raised further and further from the chance line. Thus, the results show that time and intensity do trade, but the trade is far from complete. They confirm that time and intensity differences are not truly equivalent.

In general, empirical results on clicks using the centering method show that the trading ratio tends to decrease (that is, the time delay becomes more important relative to the intensity difference) as the overall intensity level increases (David, Guttman, and van Bergeijk, 1959; Deatherage and Hirsh, 1959; Harris, 1960; Hafters and Jeffress, 1968) and as the frequency content of the click is lowered (Harris, 1960). Studies on

effects of interaural time-intensity difference combinations for tones have also been carried out widely. Sayers and Cherry (1957) demonstrated the effect of interaural intensity differences on the coherence curve, and obtained judgements of sidedness for an 800-Hz tone. The coherence curve shrank when the interaural difference in intensity increased to about 30 dB. Sayers (1964), with the use of a visual scale, obtained a lateralization curve as a function of interaural delay. An additional interaural intensity difference shifts the whole curve toward the side for the ear which receives the more intense stimulus.

Jeffress (1971) has proposed that there are at least two mechanisms for lateralization, one of which operates on both interaural time delays and interaural intensity differences over the entire audible frequency range. The other is little affected by interaural intensity differences but operates on interaural time delays over the range below 1500 Hz. This argument agrees with the general concept of the 'duplex theory'. The studies on lateralization of filtered clicks (Yost, Wightman, and Green, 1971) also showed that the most accurate lateralization was for stimuli below 1500 Hz. This might be because in the low-frequency range, information on timing of the 'fine structure' of the waveform on the basilar membrane is available for comparison at the two ears. For high-frequency stimuli, the fine structure information will be lost, and only the information from the waveform envelopes can be used for comparison.

### E. Models of Binaural Interaction

Although a large number of studies have been concerned with characterizing the transformation from stimulus to response in binaural experiments, a complete and adequate description of subjective lateral image position and the statistical properties of the entire subjective position space is still not available. Besides, an explicit, quantitative, applicable binaural model, which can be used to explain the basic physiological or functional mechanism for lateralization, as well as other phenomena, has not been established. In this section, some of the existing models which are directly related to auditory lateralization and their applications to empirical results will be discussed. Some of them will be reconsidered, if appropriate, in the Discussion Section with respect to the results of this study.

#### 1. Count-Comparison Models:

First of all, a group of count-comparison models will be considered. In these models the lateral image position is determined by comparing the activity levels in two neural populations. The first of this group was proposed by Békésy (1930). He assumed that there is a population of nerve cells that are innervated by nerve fibers from both ears. Any single nerve cell will be tuned to one of two excited states according to the source of stimuli. Generally, a cell is tuned right by the stimulus at the right ear and tuned left by the

stimulus at the left ear. The degree of lateralization is determined by comparing the count of cells right with the count of cells left. In other words, the image position is determined to the right, at the center, or to the left depending on whether the number of cells tuned right is greater than, equal to, or less than the number of cells tuned left. Thus, if a binaural stimulus contains only interaural intensity differences, the input from the more intensive side will tune more cells compared with the other side and the image will be lateralized on the side with the more intense input. For impulsive stimuli and stimuli containing information about interaural time differences, Békésy extended his model by assuming that the input stimulus at each ear causes a wave of excitation to sweep through the cell population. The excitation wave will tune cells depending on the source of the wave until the two waves from opposite sides meet and extinguish each other. Thus, if a binaural stimulus contains an interaural time delay, the excitation wave from the delay side will be extinguished before it reaches the center of the cell population (i.e., the two waves will meet away from the center of the cell population, towards the side with the delayed wave), more cells will be tuned to the opposite direction, and the image will be determined toward the side whose input arrived earlier.

Matzker (1958), by considering its consistency with anatomical and electrophysiological data, replaced Békésy's

population of tunable cells by two symmetric auditory pathways, and proposed that lateralization is determined by a comparison between activity levels at some higher central nucleus. He also assumed the existence of contralateral inhibitory pathways, and that firing of an inhibitory fiber will delay the transmission of firings along excitatory fibers; thus, the inhibitory mechanism increases the asymmetry of response levels. Further, by the effect of the inhibitory mechanism, for impulsive stimuli, an interaural time delay also results in an asymmetry of responses in the two pathways, since inhibition will be increased on the pathway receiving the delayed stimulus and decreased on the pathway receiving the advanced stimulus. Van Bergeijk (1962) reconstructed Békésy's idea by assuming that the binaural interaction occurs at a relatively peripheral pair of nuclei, i.e., the accessory nuclei of the superior olive, and that lateralization is determined by comparing the number of neural firings in those two nuclei. In addition, differing with Matzker, for any nucleus, ipsilateral inputs are inhibitory and contralateral inputs are excitatory, and, thus, an image will be lateralized to the side of the nucleus with the lesser number of firing. For example, if the stimulus at the right ear leads in time, the excitatory firings will arrive earlier than the inhibitory firings at the left nucleus, and more neurons will be excited on the left. Thus, a binaural stimulus with the right input leading in time will have an

image lateralized to the right.

In general, the mechanisms of count-comparison proposed by Bekesy, Matzker, and van Bergeijk are qualitative rather than quantitative and are, therefore, of restricted applicability; they do not specify internal noise, and are concerned with lateralization only at a very simplistic level. In order to extend those concepts to a more physiological basis, Hall (1965) measured the electrophysiological responses of single nerve cells in the accessory nucleus of the superior olive in the cat. Acoustic clicks were presented through earphones to the two ears of anesthetized cats and the stimulus parameters investigated included interaural time difference, interaural intensity difference, and average intensity. Attention was focused on a particular class of cells (named 'time-intensity trading cells') which are excited by stimulation of the contralateral ear and inhibited by stimulation of the ipsilateral ear (Galambos, Schwartzkopff, and Rupert, 1959; Moushegian, Rupert, and Whitcomb, 1964). The inhibition of ipsilateral stimulation is important because the degree of inhibition is a function of both the interaural time delay and the interaural intensity difference. The experimental results were then incorporated into van Bergeijk's model of binaural interaction, for which it was postulated that localization judgements are obtained on the basis of a comparison of the amounts of response activity in the two accessory nuclei. The model

yielded predictions that are in agreement with results from human psychophysics (David, Guttman, and van Bergiejk, 1959), where the virtual image is lateralized toward the side receiving prior or more intense stimulation. A time-intensity trading relationship derived from the model can be used to explain lateralization based on interaural time differences. The prediction is in agreement with empirical results from 'centering' experiments (David, Guttman, and van Bergeijk, 1959).

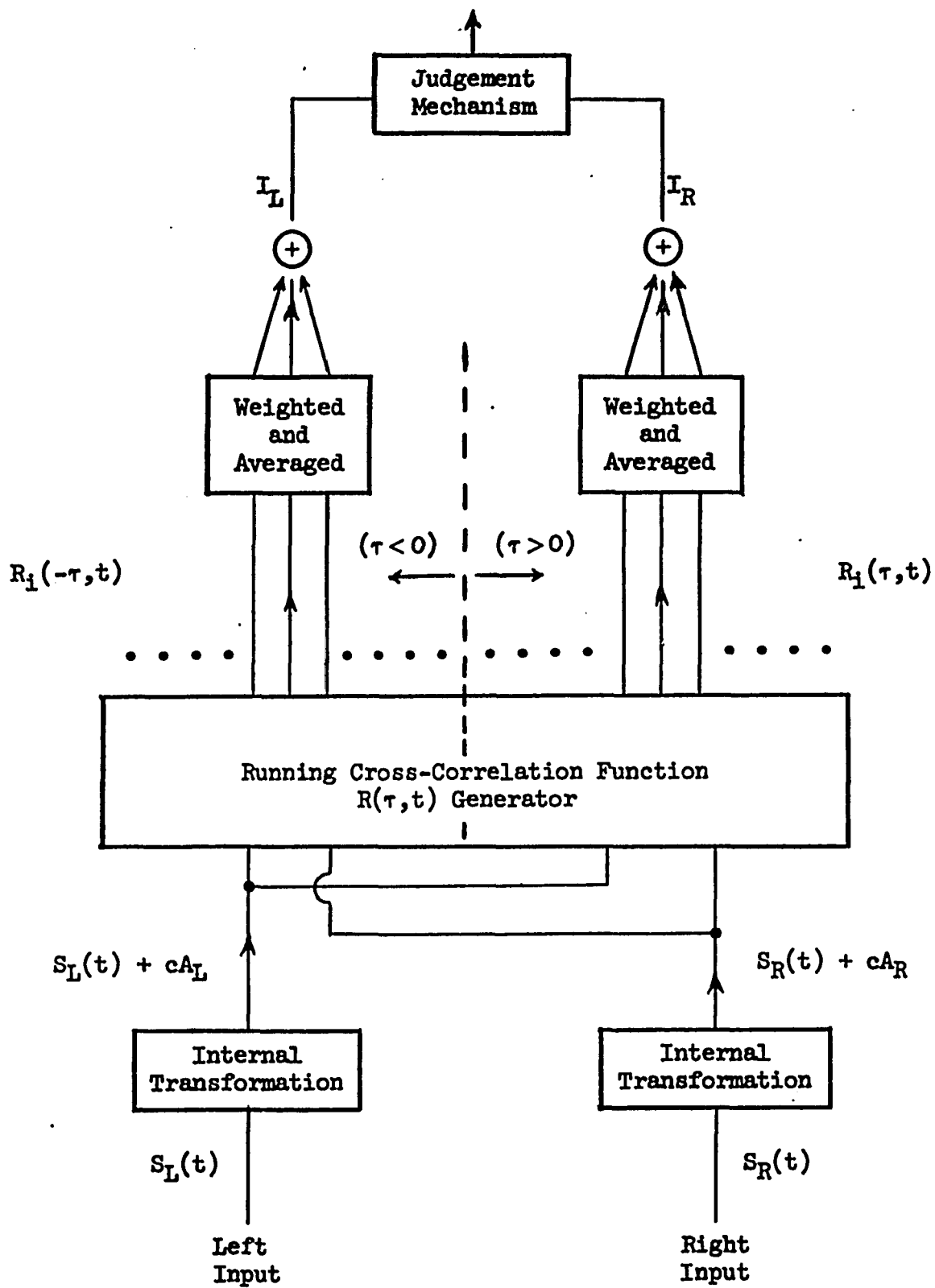
Furthermore, Hall also considered the variability observed in his physiological data and the implications of this variability for interaural discrimination. He proposed that the input signals and the responses of cells are statistically independent from cell to cell and from trial to trial and that there is no memory from trial to trial. Thus, the probability of firing response for a given cell is constant from trial to trial and is independent of the firings on other trials or in other cells. Again, Hall did not consider the basic physiological mechanisms governing the behavior of the time-intensity trading cells and did not determine the extent to which the effects of interaural intensity differences were caused by the dependence of latency on intensity at the periphery (where intensity differences are effectively transformed into time differences).

## 2. Cross-Correlation Models:

Based on their study of binaural fusion and lateralization, Sayers and Cherry (1957) proposed a cross-correlation model to describe the mechanism of binaural fusion as a form of statistical operation based upon the brain's execution of a running cross-correlation of the input signals from the two ears. Since a binaural image is generally more fused when the binaural inputs are more alike, and since correlation is a proper measure of the degree to which waveforms are alike on a point-to-point basis, it is natural to attempt to describe binaural fusion in terms of interaural correlation. For complex stimuli, this argument is still consistent since the binaural system can select the stimulus components that are common to both ears and the relative influence of a particular common component in a complex stimulus is proportional to the product of the levels of the component at the left and right ears. A block diagram of this simple cross-correlation model of binaural fusion is presented in Figure 6.

The basic argument of this model can be briefly described as follows. The input signals at the two ears,  $S_L(t)$  and  $S_R(t)$ , are first transformed by adding to each a dc term,  $cA_L$  or  $cA_R$ , which is directly proportional to signal level, where the constant,  $c$ , is postulated to be much greater than unity. The two transformed input signals then undergo a running cross-correlation, i.e., pass through the running function,  $R_1(\tau, t)$ ,

Figure 6. Block diagram of cross-correlation model proposed by Sayers and Cherry (1957). The parameters  $A_L$  and  $A_R$  are the averaged levels (rms values) of the inputs. The constant  $c$  in the initial transformation is postulated to be much greater than unity. For a detailed explanation, see text.



transform. The output of the running cross-correlator is a continuous function of time,  $t$ , and of internal interaural delay,  $\tau$ , although the output in the  $\tau$  dimension is represented here as a set of discrete outputs. The running function is then weighted by two factors. (1) It is weighted by the magnitude or level at the left ear for interaural delays less than zero, and by the magnitude or level at the right ear for interaural delays larger than zero. (2) It is also weighted by  $e^{-k|\tau|}$  and the two halves of the curve (i.e.,  $\tau < 0$ ,  $\tau > 0$ ) are integrated from  $\tau = 0$  out to  $|\tau| = |\tau_{\max}|$ , such that  $e^{-k|\tau_{\max}|}$  is small. This operation produces the integrals  $I_L$ ,  $I_R$ , for  $\tau < 0$ ,  $\tau > 0$ , respectively. In other words, the resultant function corresponding to each value of the internal interaural delay,  $\tau$ , is weighted by two factors, one dependent on the polarity of the delay and the second on the magnitude of the delay. The functions are then time-averaged, the outputs with common delay polarity are added together, and a judgement function is computed as the difference of those two sums (each based on common delay polarity). Finally, judgement of interaural position is generated by a judgement mechanism based on the results of the judgement function. Basically, the cross-correlation function of two input signals is first established. The weighted resultant is held to describe the fused sound image. The judgement mechanism then operates on the time-averaged and weighted resultant to produce the judgement of lateral image position.

(Note that the operation of integration in the original model is denoted by a '+' sign in Figure 6).

Sayers and his colleagues have applied the basic model, as well as some revisions, to a wide variety of fusion and lateralization data (e.g., Sayers and Cherry, 1957; Leakey, Sayers, and Cherry, 1958; Cherry and Sayers, 1959; Sayers, 1964; Sayers and Toole, 1964; Toole and Sayers, 1965a, 1965b). The empirical results described by the model included binaural-coherence-curve data, results from lateralization-scaling experiments, and the effects of interaural intensity discrimination. However, it must be pointed out that, for lateralization based only on interaural intensity differences, the image position depends heavily on the direction of an interaural amplitude imbalance. The correlation function derived from the model depends only on the product of the amplitudes of the two functions being correlated and does not consider how this product is decomposed into factors. It seems that, in addition to the running cross-correlation function, which is a function of time,  $t$ , and interaural delay,  $\tau$ , a mechanism to describe interaural intensity effects must be included. A more recent study by Sayers and Lynn (1968) made an attempt to study interaural intensity effects on lateralization with low-pass filtered binaural clicks, in order to minimize the risk of interference from multiple images arising with wide-band transients. The time-intensity trading relations that are

derived from physiological experiments on the cat (Kiang, 1965) were compared with their results obtained from behavioral centering experiments on man. It was found that, for auditory-nerve fibers, the rates of change with intensity of the center of gravity of post stimulus time histograms are approximately the same as the behavioral trading ratios. This led them to propose that, for transient stimuli, experimental procedures that allow judgement-averaging (e.g., a centering task) measure intensity effects that are caused by averaged neural responses, while the experiments tracing single images without judgement-averaging (e.g., a lateralization-judgement paradigm introduced by Sayers (1964)) show intensity effects that may be caused by mechanisms in the higher centers of the auditory pathway.

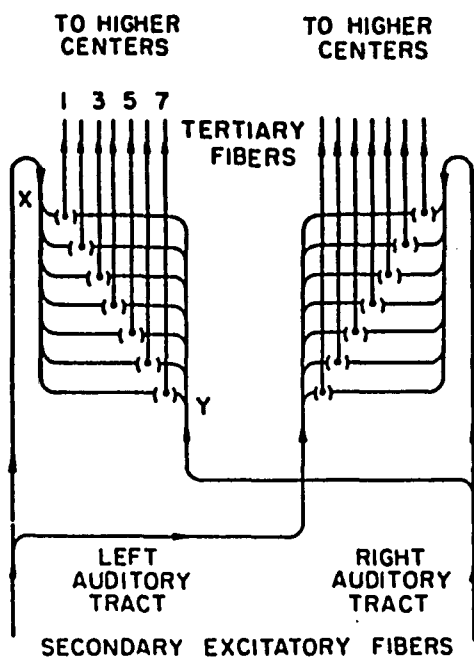
### 3. Lateralization Models:

Another group of models assumes that the binaural system can analyze, mainly, interaural differences in time and, in some cases, intensity, to determine lateral image position, as well as to improve detection in binaural masking conditions (Colburn and Durlach, 1978). Most of these models were based upon earlier work, i.e., a place theory by Jeffress (1948) of lateralization which emphasized temporal cues. The formal statement of the concept was first proposed by Webster (1951) and was considerably elaborated by Jeffress, Blodgett, Sandel, and Wood (1956), then extended by Hafter and Carrier (1970),

as well as by Henning (1973). Some of these models are applied primarily to detection (BMLDs) and some are directly related to lateralization phenomena. The discussion presented here will be mostly focused on the latter.

Figure 7 represents a hypothetical neural network outlined by Jeffress (1948). An interaural time difference can be converted into 'place information', i.e., information that is contained in the average rates of firing of neurons, as opposed to the detailed time patterns of firings. A brief description of the basic argument is as follows. A set of symmetric tertiary neurons (seven are assumed in Figure 7) are arranged in parallel. Because of the symmetry, attention can be confined to the left complex of tertiary fibers. Suppose binaural stimuli are delivered to the two ears without any interaural differences, then the two auditory tracts will be symmetrically and simultaneously stimulated. Thus, nerve impulses arrive at point X and point Y simultaneously with equal firing rates. This applies for the nerve cell of Tertiary Fiber 4. At Cells 3, 2, and 1, impulses from right-tract arrive progressively later than impulses from the left-tract, and at Cells 5, 6, and 7, progressively earlier. It is also assumed that more nearly coincident stimulation is more effective in evoking a response from a cell than less nearly coincident stimulation. Thus Cell 4 will respond maximally compared with the others. The place information in the network will be at the center, when

Figure 7. Neural network proposed by Jeffress for localization of low-frequency tones. The tertiary neurons act as coincidence detectors: a tertiary fiber is more likely to respond when firings from left and right secondary fibers reach the cell body at times that are closer to simultaneity. Interaural time differences in the firings of the input fibers are thus converted to differences in the spatial excitation pattern of the output fibers. The effects of interaural intensity differences are included by assuming that a more intense signal leads to earlier firings in the secondary fibers. (From Jeffress, 1948.)



the external interaural time delay is zero.

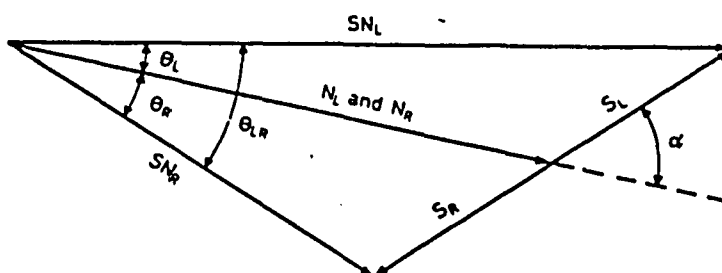
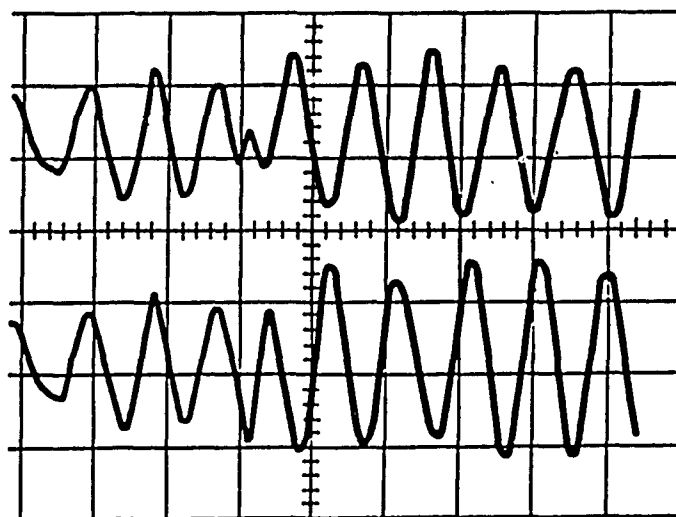
If the stimulation from the left-tract reaches the network later than the right-tract, coincidence will appear closer to point X than point Y, and the average firing rate of Cell 4 will be larger than those at Cells 5, 6, or 7; and less than those at Cells 3, 2, or 1. Thus, interaural time delay is converted into place information by the distribution of the responses over cells at different places.

Jeffress (1948) also proposed the so-called latency hypothesis which argued that interaural intensity differences are assumed to change the relative interaural time delays in the primary and secondary fibers such that a binaural stimulus that is more intense to the right ear will generate impulses that arrive earlier at point Y than at point X. Therefore, the resultant effect on neural place information in the tertiary fibers will be very similar to an external delay at the left ear as described in the preceding paragraph. Thus, Jeffress' tertiary fibers network, combined with the latency hypothesis, can be used to interpret the dependence of lateralization on both interaural time and intensity differences, as well as the concept of time-intensity trading, because, for any kind of stimulus, the tertiary fibers will provide the appropriate timing information. Note that the latency hypothesis which mediates the idea of time-intensity trading was rejected by count-comparison models (Hall, 1965).

Webster (1951), based on Jeffress' hypothetical neural network, proposed the first type of interaural-difference-detector model which was mainly applied to BMLD phenomena. He proposed that interaural time differences provide the dominant information for binaural signal detection. Webster's basic argument was built on the detection of narrow-band target signals masked by broad-band random noise. Assuming that the total input stimulus to each ear passes through a narrow bandpass filter (i.e., critical band) centered on the center frequency of the target signal, the output can be described as a sinusoid with slowly varying amplitude and phase from moment to moment. When the interaural relations of the target signal and the masking noise are different, the interaural time difference between the outputs of the narrow-band filters depends upon the presence or absence of the target signal. Based on this fact, Webster proposed that the advantages achieved in binaural detection are the result of detecting the change in interaural time delay when the signal is added.

The above argument is illustrated in Figure 8 (Jeffress, 1971). Adding a tonal signal to the noise will yield a resultant which generally shows a difference in phase and amplitude from the original noise. If, for example, adding the signal at one ear results in advancing the signal-plus-noise in phase, then, adding the same signal but reversed in phase at the other ear will retard it. Examining the top of Figure 8, oscilloscope

Figure 8. Vector diagram illustrating the addition of out of phase tones to in-phase narrow-band noise. The top of the figure shows oscilloscope traces of the signals presented to the left ear (upper) and right ear (lower). The bottom of the figure shows resultants of the vector additions. For a detailed explanation, see text. (From Jeffress, 1971.)



traces of the signal presented to the left ear (upper) and right ear (lower) are shown. The first parts of the trace (about 3 subdivisions) represent narrow-band noise alone and are identical in the two channels. Then, a tonal signal reversed in phase in one channel relative to the other is added (the rest of the subdivisions of the oscilloscope trace) and the resultant phases and amplitudes are shifted for the two channels.

The bottom of Figure 8, a vector diagram, illustrates the effects of signal added to narrow-band noise at one instance in time. The in-phase identical narrow-band noise is represented by  $N_L$  and  $N_R$ , the signal in the left channel is denoted by  $S_L$ , and the signal in the right channel, which is opposite in phase and identical in level, by  $S_R$ . The phase angle of the addition,  $\alpha$ , would vary randomly from moment to moment. The resultant stimulus in the left channel  $SN_L$ , differs from the one in the right channel,  $SN_R$ , in both amplitude and phase.

According to the Webster-Jeffress model, binaural detection is based mainly on the differences in phase and level at the two ears which result from the addition of the signal to the band of frequencies in the noise which contributes to the masking of the signal. As Jeffress (1971) has outlined, such detection appears to be an aspect of lateralization. The signal is detected because it is heard as a displacement from the noise in the median plane. Even when time and level are in opposite directions, there is a movement away from the median plane, a

movement which is detectable although ambiguous in direction. Jeffress and his colleagues have described a series of experiments on BMLDs with varieties of stimulus conditions as well as different phase angles (e.g., McFadden, Jeffress, and Ermev, 1971; Jeffress and McFadden, 1971; McFadden, Jeffress, and Lakey, 1972). Aside from the modeling concept discussed above, the research on BMLDs is not directly related to the study reported here.

Henning (1973) has worked out detailed mathematical expressions, and the relevant distributions can be computed to make specific predictions for the Webster-Jeffress model. He also specified an explicit internal noise for the model; he assumed that half-Gaussian noise contributed to the interaural phase shift and computed the form of the dependence of frequency-discrimination performance on the signal-to-noise ratio for an interaurally phase-inverted sinusoid masked by interaurally identical noise. However, results of these computations failed to describe the large release from masking obtained in masked frequency-discrimination experiments when the interaural phase of the sinusoid is changed from in-phase to out-of-phase.

Another model which is based on the Webster-Jeffress model and more closely related to this study was proposed by Hafter and Carrier (1970). By tracing the line of the thought that a change of lateral position or lateral movement is the basic cue used in binaural detection (Jeffress, Blodgett, Sandel, and Wood,

1956), they proposed a lateralization model in which the decision variable for detection is a linear combination of the interaural time difference and the interaural intensity difference with relative weights specified by the time-intensity trading ratio  $\overline{TR}$ . Generally, this conceptual model is supported not only by its consistency with lateralization phenomena (especially, the phenomenon of time-intensity trading), but also by results that show that the distribution of lateralization responses can be used to predict detection performance (Hafter, Bourbon, Blocker, and Tucker, 1969; Hafter, Carrier, and Stephen, 1973).

As has been discussed before, presenting antiphase binaural signals added to identical noise at the two ears produces interaural differences in intensity as well as in time. The traditional vector model (i.e., Webster-Jeffress model) presumes that differences in intensity do not contribute directly determined information for detection. If this is true, the vector model should predict that the BMLD will be zero at high frequencies where interaural time differences are ineffective as cues for lateralization. But studies have reported a small BMLD found at high frequencies (Green and Henning, 1969). Thus, Hafter and Carrier proposed a modification of the vector model by suggesting that detection is based on a lateral shift in the subjective auditory image produced by interaural differences in both time and intensity. It has also been assumed

that the effects of the two differences, when both cues exist simultaneously, interact and are weighted in a manner similar to that of the process of sound localization (as discussed in the previous section). It has been shown in some studies that lateralization, when based on both interaural time and interaural intensity, is a better predictor of the BMLD data than when based on interaural time alone (e.g., Durlach, 1964; Hafter, Bourbon, Blocker, and Tucker, 1969). The data collected by Hafter and Carrier (1970) also supports the lateralization model of the BMLD, in which: (i) the improvements in detection under antiphasic stimulus conditions with interaurally identical noise are based on the detectability of interaural differences in time and in intensity; (ii) interaural time differences are more effective cues than interaural intensity differences; (iii) when presented in consonance, interaural time differences and interaural intensity differences sum; and (iv) when presented in dissonance, they subtract. The subtraction of dissonant cues is not complete, leaving a residue of the interaural parameters that serves to improve detection.

The lateralization model has been limited in its ability to describe binaural detection and lateralization phenomena. Other models have been distinctly more successful in describing results in binaural detection (e.g., Colburn, 1973, 1977a; Colburn and Latimer, 1978; Durlach, 1960, 1962, 1963, 1964, 1966, 1972; Osman, 1971, 1973; Osman, Schachnow, and Tzuo, 1973;

Osman, Tzuo, and Tzuo, 1975), but they were not designed to deal with lateralization. The lateralization model is relevant here because of its conceptual structure (i.e., it is based a variable that should be responsible for subjective lateralization). However, in terms of the usefulness of the model, its limitations thus far are at least a consequence of its lack of specification of internal noise processes (Osman, Tzuo, and Tzuo, 1975; Colburn, 1973, 1977a; Stern and Colburn, 1978).

Jeffress (1972) has summarized, in a much broader outline, a binaural mechanism of detection and the BMLD that is essentially an extension and refinement of his original proposal. The argument, again, contains a coincidence structure that is spatially distributed in frequency and interaural time delay, and also one that becomes less dense away from the median plane. Neural firing is further assumed to be an important contributor to internal noise. This mechanism, proposed more recently, also differs from the one originally proposed in that it rejects the simple latency hypothesis. A model essentially following Jeffress' coincidence concept but explicitly incorporating a quantitative description of the auditory nerve firing patterns and neural noise will be discussed in the next section.

#### 4. Position-Variable Model:

Colburn, in a series of his papers (1969, 1973, 1977a, 1977b), presented an explicit quantitative model of binaural

interaction based on auditory nerve activity data, which reasonably well describes essentially all binaural detection data. The model includes an explicit description of auditory-nerve activity and a display of interaural timing information. A more recent paper by Stern and Colburn (1978) presented a model for subjective lateral position called the position-variable model which is an extension of Colburn's basic model. The model proposed a (nonphysiologically based) mechanism that generates a position variable by combining the outputs of the binaural displayer with an intensity function that depends on the interaural amplitude ratio of the stimulus. Since it is one of the simulations which motivate this study and is also directly related to this study, all details of the arguments will be discussed step by step here. Figure 9 presents a block diagram of the position-variable model as presented by Stern and Colburn (1978). Four major components of the hypothetical concept are (1) peripheral transformation, (2) monaural processor and binaural timing displayer, (3) time-intensity interaction, and (4) decision-variable generation. The details of the peripheral processors and timing displayer have been clearly described by Colburn in his original detection model (Colburn, 1973, 1977a).

The first part of the position-variable model, the peripheral processor, is a direct extension of work and techniques by Siebert (1968, 1970) on monaural phenomena.

Figure 9. Block diagram of the position-variable model.  $L_m$  denote outputs from timing displayer. The timing function  $L_T(\tau)$  is the density of interaural coincidences in auditory-nerve event times recorded by the timing displayer with respect to internal delays  $\tau$  of the fiber pairs. The intensity function  $L_I(\tau)$  is Gaussian-shaped and its location along the  $\tau$ -axis depends on the interaural intensity difference of the stimulus. The position estimate  $\hat{P}$  is obtained by computing the centroid of the position function  $L_P(\tau)$ , which is the product of the timing and intensity functions. For a detailed explanation, see text.

(From Stern and Colburn, 1978.)

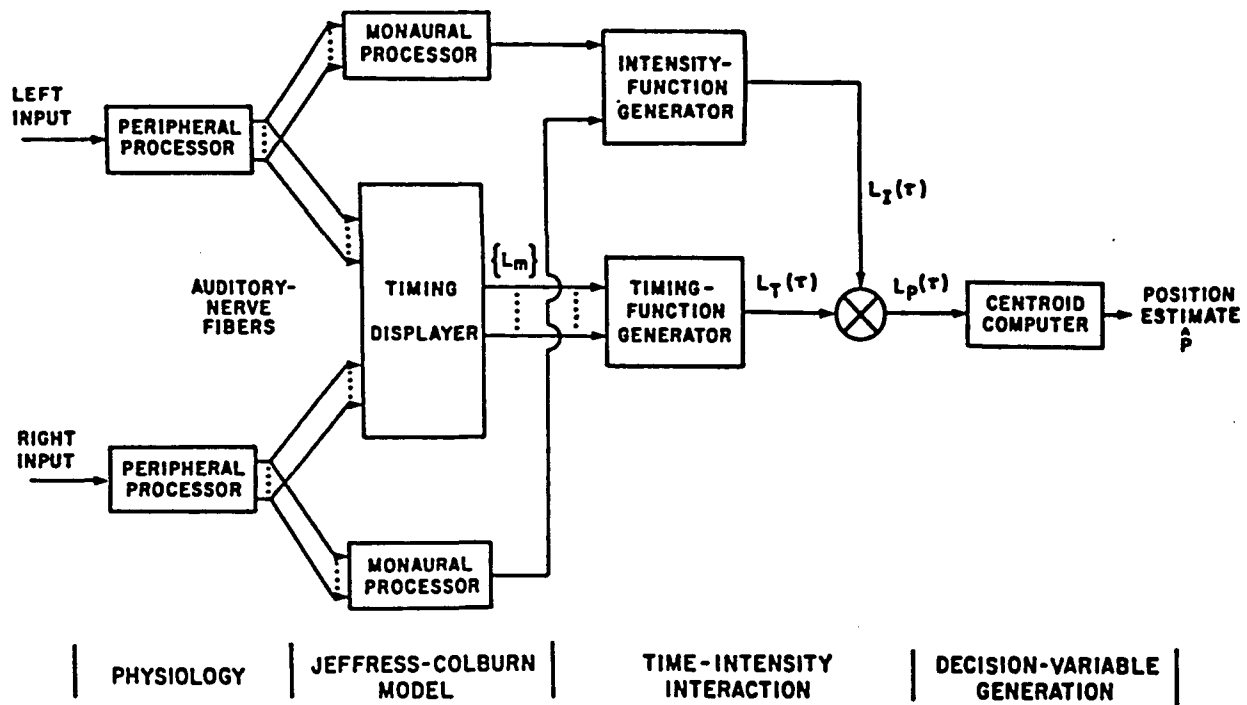
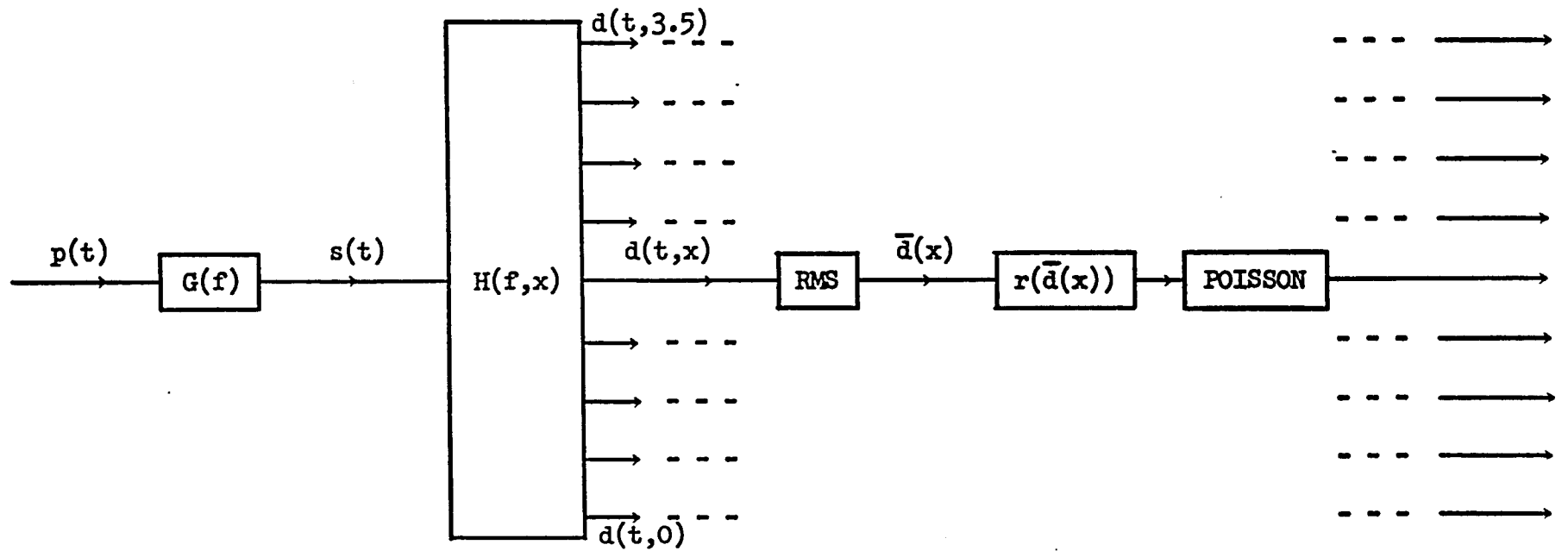


Figure 10 presents Siebert's hypothetical work and it can be briefly outlined as follows. As the auditory stimulus reaches the ear, the pressure,  $p(t)$ , in the ear canal will be first transformed by a gain function,  $G(f)$ , into the volume displacement,  $s(t)$ , of the stapes in the middle ear.  $G(f)$  can be treated as a linear time-invariant system and has roughly the characteristics of a low-pass filter with cutoff frequency about 1000 Hz, falling smoothly for high frequencies. Displacement of the stapes will then be transformed to volume displacement of the cochlear partition (i.e., basilar membrane),  $d(t,s)$ , via another linear time-invariant system,  $H(f,x)$ , where  $x$  denotes the point on the cochlear partition measured from the stapes. The characteristics of  $H(f,x)$  can be summarized as: (1) for a unit sinusoidal displacement of the stapes at frequency  $f$ , the amplitude of the volume displacement of the partition (i.e.,  $H(f,x)$ ) is maximum at the point  $x(f)$ , where  $f$  is measured in Hz and  $x(f)$  in cm. Furthermore,  $x(f)$  is approximately the inverse of  $f$ ; thus, high frequencies stimulate the basal part of the partition near the stapes and low frequencies the opposite end. The shape of the volume displacement of the partition, except for shift of origin, is almost independent of frequency. (2) The response to a unit displacement of the stapes, at a fixed point  $x$  along the partition, has a maximum at a frequency  $f(x)$  and it is approximately the inverse of  $x(f)$ . The shape of  $H(f,x)$  on a logarithmic scale, except for a choice of origin,

Figure 10. Block diagram of the model for the peripheral auditory system. For a detailed explanation, see text. (From Siebert, 1968.)



Pressure  
in  
Ear Canal

Displacement  
of Stapes

Displacement  
of Cochlear  
Partition at  
Point  $x$

Fibers of Model  
Auditory Nerve

is almost independent of  $x$ . That is, the forms of the  $H(f,x)$  functions are almost the same and parallel to each other (Siebert, 1968, Figure 4.3). Mathematical predictions by Siebert are in fair agreement with Békésy's (1960) observations of the dynamic behavior of the inner ear, and the  $H(f,x)$  functions provide a reasonably good fit to the 'tuning curves' or isorate contours measured for primary auditory neurons (Kiang, Watanabe, Thomas, and Clark, 1965).

The next block of Siebert's model is labeled 'RMS', and provides an output equal to the short-time root-mean-square value of the input,  $d(t,x)$ , and is considered to be at most a slowly varying function of time. Since the output would be substantially constant over the relevant time intervals, the time variable has been suppressed and the output of the 'RMS' block can be designated simply  $\bar{d}(x)$ , independent of time. The value of  $\bar{d}(x)$  will then be transformed by a nonlinear no-memory transformation,  $r(\bar{d}(x))$ , which provides the firing rate for each individual fiber. The last block, labeled 'POISSON' is intended to generate sample functions from independent nonhomogeneous Poisson processes (e.g., Parzen, 1962) characterized by the corresponding rate function  $r(\bar{d}(x))$ . Since this rate function will, in general, be a slowly varying function of time, these processes will, in general, be nonstationary. In summary, the sample functions generated by the modeling processes in response to a pressure wave  $p(t)$  are Siebert's

simplified model of the time patterns of firings that would be observed at some fixed point along the listener's auditory nerve in response to that same acoustic waveform.

In a more explicit way, Siebert (1970) represented his model by the following equation:

$$r_i(t, f, A, \theta_i) = r_0 \exp \left\{ G [AH(f/f_i)] \cos(2\pi ft + \theta_i) \right\} .$$

$r_i(t)$  denotes the firing rate function, or the intensity function, of a certain auditory nerve fiber, and is a periodic function of time  $t$ , and also a function of frequency  $f$ , amplitude  $A$ , and phase angle  $\theta$  of the input signal. The fact that it is a periodic function of time is determined by the cosine term, which generates a representation of the phase-locking seen in auditory neuron responses at low frequencies (Kiang, Watanabe, Thomas, and Clark, 1965; Rose, Grugge, Anderson, and Hind, 1967).  $r_0$  denotes the rate of spontaneous firing and is assumed to be a constant of magnitude about 50 impulses/sec for any fiber. The time pattern of real spontaneous firings is irregular, but it is reasonable to assume that the successive intervals between firings are statistically independent variables. Physiological data in the form of interval histograms of spontaneous firings for single fibers (Kiang, Watanabe, Thomas, and Clark, 1965) are well fitted by the exponential function.

In the equation, the gain function,  $G$ , and volume displacement function of the stapes at the frequency of

stimulation,  $H$ , have been described above. In addition,  $H$  is a function of stimulus frequency,  $f$ , and the characteristic frequency,  $f_i$ , of a given fiber, and it gives a simple approximation to the fiber tuning curves that show the frequency selectivity of the individual nerve fibers, including the dependence of the sharpness of such tuning curves on the characteristic frequency of the fiber.  $\theta_i$  is the (fiber dependent) phase parameter of the input signal. Siebert did not include this parameter in his original hypothetical construction of his model (Siebert, 1968), but since information provided by the phase angle could be useful for listener's judgements, especially in a discrimination task, he later added this parameter in the equation. Finally, firing patterns of individual auditory-nerve fibers are assumed to be sample functions from stochastic point processes (i.e., random discrete processes). This is essentially based on the well-known all-or-none description of neural firing that is implicitly assumed by most neural physiologists, and the neural data can be adequately described by using a nonhomogeneous Poisson process.

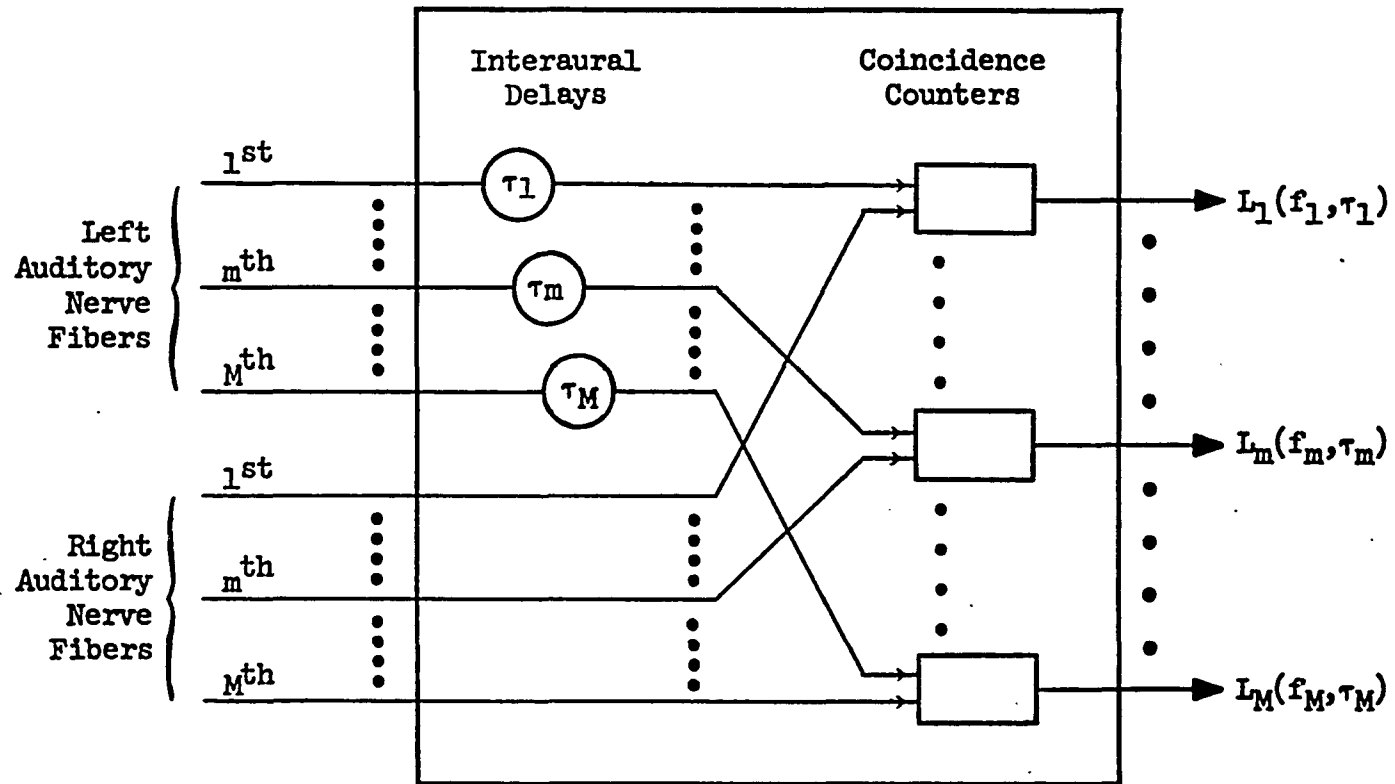
Siebert's model of auditory nerve firing patterns applies at best to a very restricted class of stimuli, such as sinusoidal tone bursts of limited durations, intensities, and frequencies. By comparing the monaural results from human listeners to the computed limiting performance from his model, Siebert concluded that the listener behaves as if he ignores

the periodicity information in the auditory-nerve pattern (resulting from the phase-locking of the firings to the stimulus), but makes full effective use of the place information (resulting primarily, although not entirely, from the mechanical tuning of the inner ear).

The major component of the second part of the block diagram of the position-variable model, the timing displayer, is essentially the work of Colburn (1973, 1977a, 1977b). Figure 11 presents a possible realization of the binaural displayer (Colburn, 1977a). It is similar to the model of 'coincidence' or tertiary network of Jeffress (1948). The inputs to the binaural displayer are pulse trains representing the firing patterns of auditory-nerve fibers as described by Siebert (1968, 1970). Colburn retained all information about the detailed time patterns of auditory neuron firings, which are important elements for modeling binaural phenomena, as well as the source of internal noise (e.g., the randomness of the peripheral firing patterns), the peripheral bandpass filters (the tuning curves associated with individual fibers), and other dependencies on the level and spectral content of the stimulus (the dependence on these parameters of the average rate and synchrony of an individual fiber's responses). For the binaural displayer, in final form, the pulse train of each fiber undergoes an interaural delay,  $\tau_m$ , and is then compared with the pulse train of exactly one fiber from the other ear. A coincidence count is computed

Figure 11. Block diagram for a possible realization of the 'binaural displayer' presented in Colburn's binaural interaction model. For a detailed explanation, see text. (From Colburn, 1977a.)

BINAURAL DISPLAYER



of how many times pulses in these two pulse trains occur almost simultaneously. The internal interaural delays, denoted as  $\tau_m$  and shown on the left channel, are assumed to be fixed for each fiber pair and to take on positive and negative values symmetrically. It is also assumed that both of a pair of fibers have identical characteristics; in particular, they have a common characteristic frequency,  $f_m$  (the frequency to which they are most sensitive).

The outputs of the binaural displayer can be described easily by representing them on a two-dimensional grid,  $L_m(f_m, \tau_m)$ , in which one dimension is the characteristic frequency,  $f_m$ , of the fiber pair, and the other is the relative internal interaural delay,  $\tau_m$ , of the fiber pair, and the entries represent the number of counts of coincidences for the various frequencies and interaural delays. The task of the binaural analyzer is to make judgements about the stimulus on the basis of those entries. Obviously, a binaural tone having a frequency  $f_0$  results in larger output (i.e., coincidence counts) for the fiber pairs with  $f_m$  values close to  $f_0$ , since the fibers with characteristic frequencies near  $f_0$  will respond with higher firing rates. If the tone is presented with an interaural delay of  $\tau_s$ , then the outputs for fiber pairs with internal  $\tau_m$  values near  $-\tau_s$ , or near multiple periods of  $-\tau_s$ , (i.e.,  $-\tau_s + n/f_0$ ,  $n$  is an integer), are larger than the outputs associated with other  $\tau_m$  values, provided that the tone frequency is low enough that the

auditory-nerve patterns are synchronized (i.e., phase-locked) to the detailed time structure of the tone. It must be pointed out that, for high frequency continuous tones, the outputs  $L_m(f_m, \tau_m)$  of the binaural displayer are independent of the interaural phase shift of the tone; for tone bursts of high-frequency whose filtered waveforms contain a lower-frequency envelope structure, however, displayer outputs will be still dependent on the interaural delay.

It is clear from a comparison of Figure 11 with Figure 7 that the binaural displayer is very similar to the mechanism proposed by Jeffress (1948), and the position model discussed here can be considered as a quantification and elaboration of some of Jeffress' ideas. It is also clear that this model can be considered as a specific mechanism for generating a discrete function estimate of the cross-correlation function that played a central role in Sayers' cross-correlation model. In brief, the binaural timing displayer can be considered as that; it consists of a network of binaural units, each taking input from two auditory-nerve fibers with the same frequency characteristics, one from each ear, with a small fixed delay inserted on one side. Each unit counts coincidences in firing times of the two input fibers (after the delay and within a very short time interval), and these counts serve as output.

The third part of the block diagram of Figure 9 includes two function generators, the intensity-function generator and

the timing-function generator. The intensity function,  $L_I(\tau)$ , was assumed to be a deterministic Gaussian function of  $\tau$ , with a fixed width,  $W_I$ . The location of this pulse-shaped function along the  $\tau$  axis depends on the interaural intensity difference of the stimulus,  $\alpha_S$ , according to the function  $M_I(\alpha_S)$ . The parameter  $W_I$  and the function  $M_I(\alpha_S)$  were chosen by Stern and Colburn (1978) to fit the data in their own lateral-position-matching experiments (using an interaural intensity difference pointer). The timing function,  $L_T(\tau)$  is defined to be the number of coincidences occurring in response to the stimulus presentation from all fibers in a fixed range of characteristic frequencies as a function of internal interaural delay. The range of characteristic frequencies was chosen to optimize interaural discrimination performance (Stern and Colburn, 1978) predicted by the model at moderate overall levels (55 dB SPL), and is from 190-3350 Hz for 500-Hz tonal stimuli. Note that the range chosen is quite broad, and a different range of characteristic frequencies would be used to obtain predictions for stimuli at frequencies other than 500 Hz. Also note that, because the set of fibers used to compute  $L_T(\tau)$  is fixed, some of the coincidences included in the function  $L_T(\tau)$  will be from fiber pairs that may not be synchronized to the stimulus, which occurs when the stimuli are presented with low overall intensities and/or large interaural amplitude ratios. Thus, for example, the predicted value of the timing function,  $L_T(\tau)$ ,

for a 500-Hz tone burst at 55 dB SPL presented with a 500- $\mu$ sec interaural time delay is computed by assuming that all fibers pairs in the fixed range of characteristic frequencies are synchronized to the stimulus tone.

More specifically, the timing function,  $L_T(\tau)$ , is considered to be proportional to the product of the functions  $L_m(\tau)$  and  $p(\tau)$ .  $L_m(\tau)$  is defined as the relative number of coincidence counts observed by a single fiber as described before.  $p(\tau)$  is defined as the relative number of fibers. Finally, a position function,  $L_P(\tau)$ , is considered to be the product of the timing function,  $L_T(\tau)$ , and the intensity function,  $L_I(\tau)$ , as  $L_P(\tau) = L_T(\tau) \times L_I(\tau)$ , for each  $\tau$ , as shown by the 'X' in Figure 9.

The fourth and last block of the model is the centroid computer, i.e., decision-variable generation. A position variable  $\hat{P}$  is generated, which is the centroid along the  $\tau$  axis of the position function,  $L_P(\tau)$ , as

$$\hat{P} = \frac{\int_{-\infty}^{\infty} \tau L_P(\tau) d\tau}{\int_{-\infty}^{\infty} L_P(\tau) d\tau} .$$

In brief summary (referring to Figure 9), predictions from the position-variable model are almost completely determined by a single internal variable  $\hat{P}$  that is postulated to be monotonically related to subjective lateral position.  $\hat{P}$  is the centroid of the product of two functions called the timing and intensity functions, which are directly related to the corresponding interaural differences of the stimulus. The

signal inputs at the two ears are first transformed into temporal patterns of firings on auditory-nerve fibers by probabilistic peripheral processors. The temporal patterns of firing are interaurally compared by the binaural timing displayer, which generates the set of outputs  $L_m$  from which the timing function,  $L_p(\tau)$  is generated. This function is directly related to the interaural cross-correlation of the binaural stimulus and the variable can be thought of as the argument of the cross-correlation function. The intensity difference of the stimulus is generated by two separate monaural processors (a mechanism for generating the intensity-based weighting function) and is used to determine the intensity function  $L_I(\tau)$ . This function is postulated to be a deterministic, pulse-shaped function which has a fixed width (and shape) and a location along the  $\tau$  axis. Finally, the position estimate,  $\hat{P}$ , is equal to the centroid of the product of the time and intensity functions.

The model has been used to describe experimental lateralization data such as those obtained from lateralization-matching experiments (Domnitz and Colburn, 1977) quite well. It has also been used to describe other empirical data (e.g., Moushegian and Jeffress, 1959; Sayers, 1964) more accurately and over a wider range of stimulus conditions than the previous models, except for those results which suggest that low-frequency tones can generate multiple perceptual images. The predictions of the model are also consistent with the results of centering

experiments (e.g., Elpern and Naunton, 1964; Young, 1976) and laterality-comparison experiments (e.g., Yost, Tanis, Nielson, and Bergert, 1975; Molino, 1974).

One last thing must be pointed out here, and that is that the position-variable model is the only model available so far which considers the standard deviation of the lateral position estimate, and that will be directly related to the discussion of the study presented in this dissertation. The standard deviation of the position estimate of Stern and Colburn (1978) can be briefly described as one that increases (i) as the interaural intensity difference of the stimulus increases and (ii) as the interaural time delay approaches half of the stimulus period. However, it is measured in units (dB) of interaural intensity difference by the technique of Stern and Colburn (1978); a result which is not necessarily adequate as a quantification of the core concepts implicit in the model.

Four different types of models which are most directly related to lateralization phenomena have been outlined and discussed. The following is a brief summary and comparison of those models. In the count-comparison models, the internal variable is the difference in the counts in the two cell populations at which the monaurally determined patterns first come together. Interaural time difference and interaural intensity difference are assumed to have separate effects in the

cell populations. Thus, the binaural mechanism corresponding to time-intensity interaction is after the coincidence device in those models. For the Sayers-Cherry model, the internal variable is an integrated, weighted, cross-correlation function (actually, the sum of weighted coincidence outputs). The intensity effects are mediated by weighting factors, and the time-intensity interaction again is assumed to be after the correlation-coincidence operation. In Jeffress' model and presumably in the latency-version of the Hafter-Carrier lateralization model, the internal variable that corresponds to lateralization for low-frequencies is the place of maximum coincidence along the interaural delay dimension. Changes in amplitude are assumed to cause changes in the latency of the nerve-pattern inputs to the coincidence devices. Thus the binaural mechanism that corresponds to time-intensity trading is assumed to be peripheral. In the Stern-Colburn position-variable model, the internal variable,  $\hat{P}$ , is generated by combining the output of the binaural displayer with an intensity function that depends on the interaural intensity ratio of the stimulus. Again, unlike Jeffress' model, the binaural mechanism that corresponds to time-intensity trading is assumed to be central to the correlation device.

The similarity of all the models developed to describe lateralization phenomena is obvious. It is also clear that

the Stern and Colburn (1978) position-variable model (which apparently followed some preliminary modeling considerations for a position-variable in Domnitz and Colburn (1977)), is the most sophisticated and quantitatively well specified of those models, in that it embodies the basic conceptual ideas of the other models, coupled with the detailed specification of the neural noise process as derived from Siebert (1968, 1970) and utilized by Colburn (1977a, 1977b). And therein lies a powerful theoretical justification for the work of this dissertation. This dissertation was designed specifically to measure as directly as possible the detailed statistical properties of the subjective lateral position variable that is generated in response to a low-frequency binaural tone by varying interaural phase/time delay. The only experiments of its nature that have been reported are in Sayers (1964) and Yost (1973), and are of very limited use in the context of the most recent modeling efforts. The results to be described in the rest of this dissertation provide the most complete and detailed measurements of subjective lateral image position for binaural tones yet produced, and are based on the use of a mechanical pointer designed to be a direct analogue of interaural space.

In preliminary work for this study, the use of a standard comparison stimulus to help the listener as a reference in interaural space was explored. The final decision was to conduct the experiment without a standard, with a left ear

monaural standard, and with a right ear monaural standard.

Although the original idea was to use the standard to reduce experimental error related to the listener's ability to identify subjective space with the trajectory defined by the mechanical pointer, a much more important result was found in the effects of the standard on the properties of the measured interaural space. There is no literature reviewed here in relation to this problem because none exists that is directly relevant in that it could serve as introductory material. The practical and theoretical implications of the results regarding the standard stimulus are evaluated in the latter part of the discussion. Suffice it to say here that those results suggest that the major noise process operating in interaural space may not be of peripheral origin as represented in the Stern and Colburn model, and they also suggest how routine psychophysical procedures of previous binaural experiments may have been contaminated. A very strong implication of the work presented in this dissertation is that quantitative modeling efforts by binaural theorists, as epitomized by the position-variable model of Stern and Colburn, have been on a wrong or at least limited track. Much more attention must be devoted to quantitative and stochastic representations of higher cognitive processes in binaural hearing.

## II. METHODS

The experiment was conducted to study listeners' subjective lateral position judgements of short tone bursts with interaural phase (time) differences, where either the right ear was leading in phase or the left ear was leading in phase. A set of magnitudes of phase differences was selected in order to cover a wide range of interaural phase delays. A two-interval paradigm was used in which the first interval served as a standard (reference) interval and the second interval served as a signal (test) interval. The complete details of the experiment are described as follows.

### A. Subjects

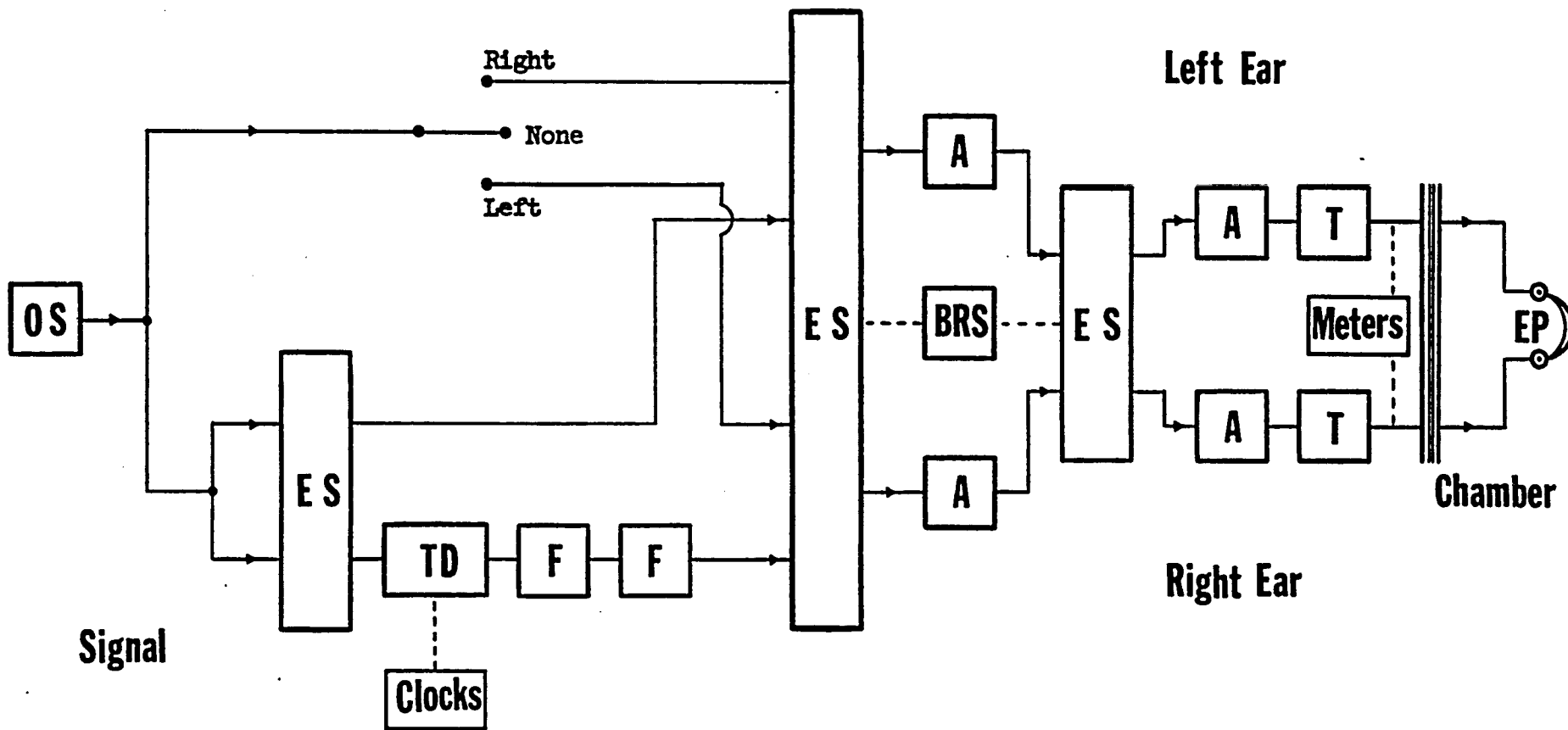
One female and one male (the author, HT) adult served as subjects. Both had normal hearing and considerable experience in psychoacoustic tasks over the past several years, and each had received long term (about two months) intensive training for this particular experiment before the data were formally collected.

### B. Apparatus

A block diagram of the basic stimulus generation and control system is shown in Figure 12. All stimuli were generated by the same audio oscillator (General-Radio 1309-A). The

Figure 12. Block diagram of apparatus. (A - attenuator,  
BRS - BRS Control Logic, ES - electronic switch,  
EP - earphones, F - filter, OS - oscillator,  
T - Transformer, TD - time delay unit.)

# Standard



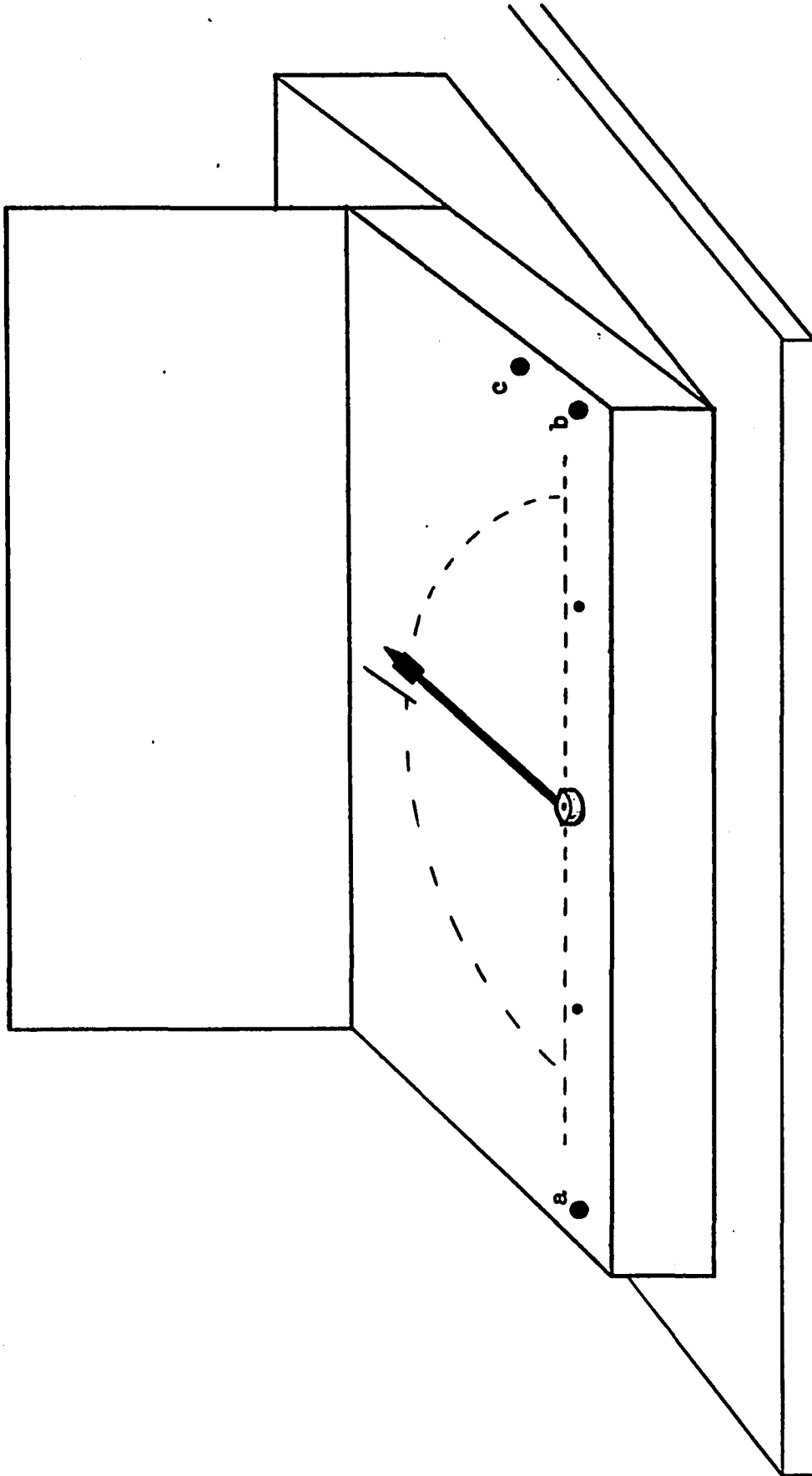
sinusoidal signal (test) stimulus was divided into two isolated channels by an electronic switch (Grason-Stadler 829E). On the left channel, the signal passed through a second electronic switch, an attenuator (General-Radio 1450), another electronic switch, another attenuator (Daven 693), a transformer (Grason-Stadler E10589A), and then to the earphone (Telephonics TDH-39) inside the double walled sound-proof chamber (Industrial Acoustics Company, Inc.). The sequence was similar for the right ear channel, except that the signal passed through a time delay unit (Reticon 931-0021) and two filters (Krohn-Hite 3202-R) before reaching the second electronic switch. Four function generators (Clarke-Hess 743) were set up to serve as a clock device which was connected to the time delay unit to provide four different interaural phase delays. The activation of one of the four function generators was controlled by a PDP-11 minicomputer program with a fixed 0.25 probability for each generator in any given trial.

The standard (reference) stimulus passed through a selector switch (to determine which standard condition was used), an electronic switch, an attenuator, another electronic switch, another attenuator, a transformer, and then to one of the listener's earphones. Two electronic switches and a series of BRS univibrators were used to control the durations of the two stimulus intervals and their temporal relations in a given trial. The earphones used in this study were a matched pair

with almost identical frequency response curves. The temporal parameters for each trial, the intensity level of the stimuli, and the interaural phase differences were carefully measured and adjusted frequently by using a dual-beam oscilloscope (Tektronix 502A), an RMS voltmeter (Ballantine Laboratories 320A), and a phase meter (Krohn-Hite 6200A) at the input to the earphones, outside the sound-proof chamber.

The response manipulandum is shown in Figure 13. A rotatable mechanical pointer, attached to a linear potentiometer, was placed on a flat panel with a continuous semi-circular scale representing positions along the surface of the head (in the mid-frontal plane). It was used to generate an analogue representation for each listener's judgements of interaural lateral position. A stable 6 volts source was placed across the potentiometer and the voltage read-out was determined by the position of the mechanical pointer. This output was fed into an analogue input channel of the LPS-11 laboratory peripheral system of the PDP-11 minicomputer, leading to maximal (approximately 1.5K) resolution of the digital representation of the scale. Three pushbutton switches were placed on the pointer panel as shown in Figure 13. One was on the left side and served as a start button, allowing the listener to initiate each trial. The second was on the right side and served to activate the reading of the position judgements by the computer. The third was also on the right

Figure 13. Drawing of the mechanical device used by the listener for communicating lateral image position judgements. Three pushbutton switches have functions as follows: a - trial starter, b - sample taking, c - reset.



and allowed the subject to reset the equipment between trials. A vertical straight line was marked at the top of the semi-circular path of the tip of the pointer (with about one-half inch of overlap with the tip). It served as a reference line to allow the listener to return the pointer to the center position after each trial.

In order to ensure its linearity, the position response system - including the mechanical pointer, the potentiometer, and the digital-output of the computer's A-D transform - was measured and calibrated very carefully in two different ways. (1) A computer program was used to allow the computer to read 1,000 samples (one sample read every 500 msec) automatically at a given pointer position. Then the mean and the standard deviation of these 1,000 samples were calculated. (2) At a given pointer position, the experimenter manually activated the computer to read in one sample by pushing a pushbutton about every 2 seconds. The mean and the standard deviation were determined from 100 samples. Each of a set of 19 selected positions, which covered a full semi-circular line from the left side ( $0^{\circ}$ ) to the right side ( $180^{\circ}$ ) of the head in  $10^{\circ}$  steps, were measured again and again. The results, provided by employing both methods, showed a very reliable and satisfactory linearity of the relation between the pointer position and the digital-output of the A-D transform.

Table 1 presents two selected sample sets of such calibration

Table 1. Two selected sample results of the measurement of the linearity of the pointer position and the A-D digital-output. For a detailed explanation, see text.

Pointer Position (from left side)	Sample Reading: Manual Calibration Procedure	Sample Reading: Automatic Calibration Procedure
0°	2249	2230
10°	2353	2332
20°	2445	2432
30°	2550	2533
40°	2644	2625
50°	2734	2715
60°	2826	2807
70°	2906	2877
80°	2987	2967
90°	3062	3040
100°	3134	3110
110°	3202	3179
120°	3278	3256
130°	3354	3333
140°	3423	3408
150°	3500	3478
160°	3571	3549
170°	3649	3626
180°	3719	3698
Correlation *	.9981	.9981

\* 'Correlation' refers to the correlation coefficient between pointer position and sample reading.

data, one from each of the two different methods. The results provided by both methods showed very high linearity and the two correlations between the position of pointer and the digital-output of the A-D transform were both 0.9981. Furthermore, the calibration results (Table 1) obtained by using the manual method were also used to serve as a transform to translate the listener's response data (digital-output) into the corresponding values of that listener's subjective lateral image positions in degrees in the processing of all results for the experiment.

Generally, the listener was seated comfortably inside the sound-proof chamber with the mechanical pointer panel placed (and adjusted to a proper height) directly in front of her/him. A dim light was placed directly behind the listener and the pointer panel was adjusted at an angle of about  $30^{\circ}$  (see Figure 13), so that the shadow of the head nearly coincided with the semi-circular path traversed by the tip of the pointer. This design served to make the listener's task much easier. The arrangement of having only this one dim light inside the chamber served to help the subject to concentrate on the pointer panel and minimized all undesirable effects from other irrelevant visual stimuli.

## C. Procedure

### 1. Experimental Design

The signal (test stimulus) and the standard (reference stimulus, when it was used) were each 250-Hz tones having a total duration of 50 msec with 10-msec rise/fall times. The intensity level for all stimuli (including the standard) was set to 70 dB SPL throughout the entire experiment. The listener initiated each trial by closing a switch, after which there was a 1,200-msec waiting period followed by a 50-msec standard interval, then a 500-msec waiting period followed by another 50-msec signal interval, and then an open response interval.

The major parameter of this study was the interaural phase difference,  $\theta$ , of the tone burst, with either the left ear or the right ear leading in phase. Thus, for this particular 250-Hz tone burst, a selection was made from a set of widely spaced interaural differences expected to cover most of the lateral extent of subjective interaural space. The set included 16 values, 8 with the left ear leading in phase and 8 with the right ear leading in phase, with absolute magnitudes of  $5^\circ$ ,  $10^\circ$ ,  $15^\circ$ ,  $20^\circ$ ,  $25^\circ$ ,  $45^\circ$ ,  $65^\circ$ , and  $105^\circ$ , respectively.

For any given interaural phase difference, on each trial, the subject's task was to judge the lateral position of her/his subjective image. Thus, there might be a subjective effect such that she/he would place the pointer at the same or within a fixed region of the lateral image space if she/he could eventually know that there was only one kind of stimulus (with

a fixed interaural phase delay) during a sequence of trials. In order to avoid this undesirable effect, a special arrangement was made as follows. For a particular nominal interaural phase difference, four values of interaural phase delay in that region were selected. They had to be sufficiently closely spaced so that the phenomenal positions of binaural tones with those delays were confusable. Thus, the spacing was to be about the size of the jnd for a shift in interaural delay. The four values of interaural phase delay for any given nominal interaural phase difference were, in fact, always spaced apart using  $2^{\circ}$  steps, which is a good estimate of the magnitude of that jnd, (Mills, 1960; Hershkowitz and Durlach, 1969; Domnitz, 1973), and were spaced uniformly around that particular nominal (average) phase difference. Thus, for a nominal delay of  $10^{\circ}$  (i.e.  $\theta = 10^{\circ}$ ) the four stimuli would have interaural delays of  $7^{\circ}$ ,  $9^{\circ}$ ,  $11^{\circ}$ , and  $13^{\circ}$ . These four binaural tonal signals were eventually presented in random order, trial by trial, and the distribution of position judgements was determined for each after many psychophysical trials. This was accomplished by a minicomputer program which sorted the data in accordance with stimulus parameters, and then generated frequency distributions of position judgements for each type of stimulus. These four distributions were then collapsed into one distribution, a procedure which is justified because of the proximity of the four delay values. This was also accomplished by a computer

program, which collapsed data over different stimulus parameters, and then generated a combined frequency distribution of position judgements for a given nominal interaural delay value.

Specifically, collapsing was accomplished by shifting each of the four contributing distributions by an amount equal to its respective deviation from the overall mean (i.e., so that the four distributions would have a common mean), and then pooling all the frequency values as one overall distribution. The entire process was repeated for all different selections from the set of widely spaced nominal interaural phase delays. Data were adjusted for response variance due to positioning of the mechanical pointer (see the following section on Data Analysis).

Three conditions of standard were used: (1) a monaural tone at the left ear (image fully lateralized at the left side), (2) a monaural tone at the right ear (image fully lateralized at the right side), and (3) a silent interval (no standard). There were, therefore, a total of 48 stimulus conditions, 16 nominal interaural phase differences x 3 standards, for which position distributions were to be determined for each subject. (Considering the four actual phase delays used for each of the 16 nominal delays, there was a total of  $192 = 48 \times 4$  individual position distribution data sets collected for each listener.) The order of data collection for the 48 stimulus conditions was randomized in the same way for the two listeners, with the 16 interaural phase differences and 3 standards mixed together.

The data were collected in blocks of 100 consecutive trials. The procedure for each of the 48 stimulus conditions was replicated four times, so that a total of 192 blocks of trials was run for each listener. Consequently, a total of 400 trials determined each nominal position distribution of the lateral image space for each subject.

## 2. Psychophysical Methods

The listener was verbally instructed as to task requirements and stimulus conditions and then was seated in the sound-proof chamber wearing the TDH-39 earphones. The experiment was self-paced, since the listener chose when to press the operate button which started each trial. Immediately after the stimuli were presented, there was an open response interval. During this response interval, the listener's task was to position the mechanical pointer so that it coincided laterally with the location of the subjective image, then press a button to activate the reading of the judgement by the computer, then return the pointer to its central location (marked by a straight line), and finally reset the equipment for the next trial by pushing another button.

After the subject finished all 100 trials of a block, the experimenter reset the PDP-11 minicomputer and equipment and then signaled the subject to start the next block of trials. A computer program was used to partially control equipment and

record data, including all relevant information such as stimulus parameters, subject's name, date and time for which the data were collected, etc. For each stimulus condition, data for four consecutive blocks were collected in a continuous fashion and the subject was only allowed to take a very short break between any two blocks, without taking off the headphones.

The experiment was conducted for each subject for about two to four hours each day. Thus, two to three stimulus conditions could be finished within one day and consequently it took about three months to run the entire experiment. Each subject was required to take about, at least, 15 minutes rest between consecutive blocks for any two different stimulus conditions, and also was allowed to have a few warm-up trials when each new stimulus condition was started. This experiment was especially difficult for the listeners so that proficiency on the tasks required extensive training. Before any data were formally collected, each subject had received about two months of training on the experimental task.

### 3. Data Analysis

For each subject and each stimulus condition, four blocks of data were stored on an RK05 disk of the PDP-11 minicomputer. These data were stored in the form of the trial by trial digital-outputs of the A-D transform associated with responses to the corresponding stimulus parameters (four values of phase shifts

for a nominal  $\theta$  value). Based on these four blocks of data, four separate frequency distributions of position judgements were generated according to actual phase shift, and the mean and the standard deviation of each were then determined. Furthermore, the correlation between the four actual values of phase shift and their corresponding mean digital-outputs was also calculated. These four position distributions were then collapsed into one combined distribution which was used to represent the listener's subjective lateral image position judgements for that particular nominal interaural phase difference. The mean,  $\bar{P}$ , and the standard deviation,  $\sigma_p$ , of each combined distribution for any nominal phase delay were also calculated.

Figure 14 represents a sample of four separate frequency distributions for four actual phase shift values of  $12^\circ$ ,  $14^\circ$ ,  $16^\circ$ , and  $18^\circ$  (for subject HT, with the left ear leading in phase, and the right standard). Figure 15 shows the corresponding combined distribution (nominal  $\theta$  value of  $15^\circ$ , left ear leading) derived from Figure 14. Figure 16 represents a sample diagram providing detailed information on the data analysis of the position judgements for the above stimulus condition. A total of 48 sets of these three types of figures were generated for each subject.

The mean,  $\bar{P}$ , and the related standard deviation,  $\sigma_p$ , determined from the digital-output data were translated into degrees by using a linear interpolation method and the manual

Figure 14. Sample of four individual histograms of subjective position-judgements for four actual interaural phase shifts, denoted  $\theta_i$ ,  $i = 1, 2, 3, 4$ , (resulting from their random presentation). Interval spacing is chosen as  $2^\circ$ , and means of each set of position-judgements,  $\bar{P}$ , are marked by vertical dashed lines.

Subject: HT     $\theta = 15^\circ$  (Left ear leading)    Standard: Right    Spacing:  $2^\circ$

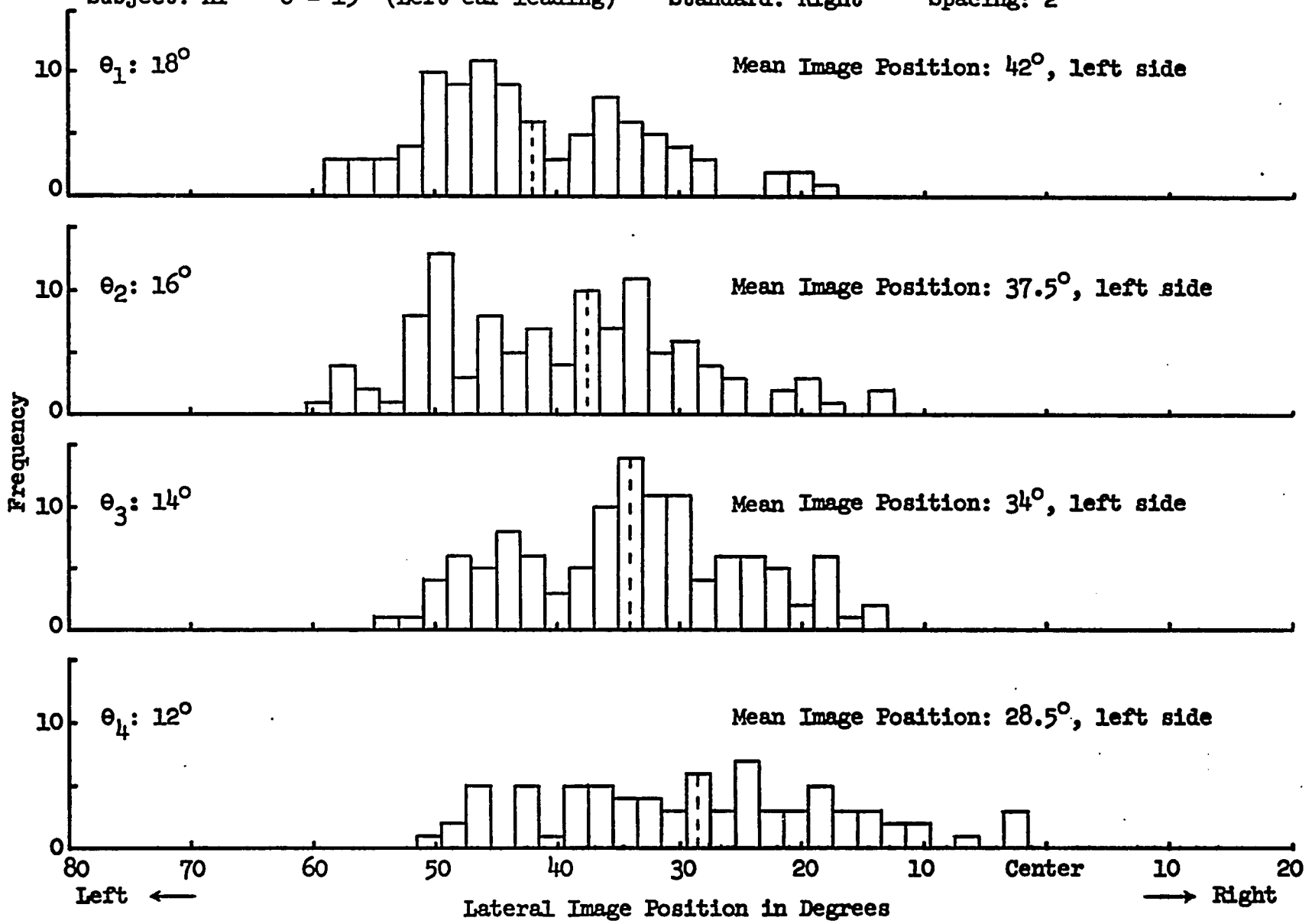


Figure 15. Sample of the histogram of subjective position-judgements for the combined data of Figure 14.

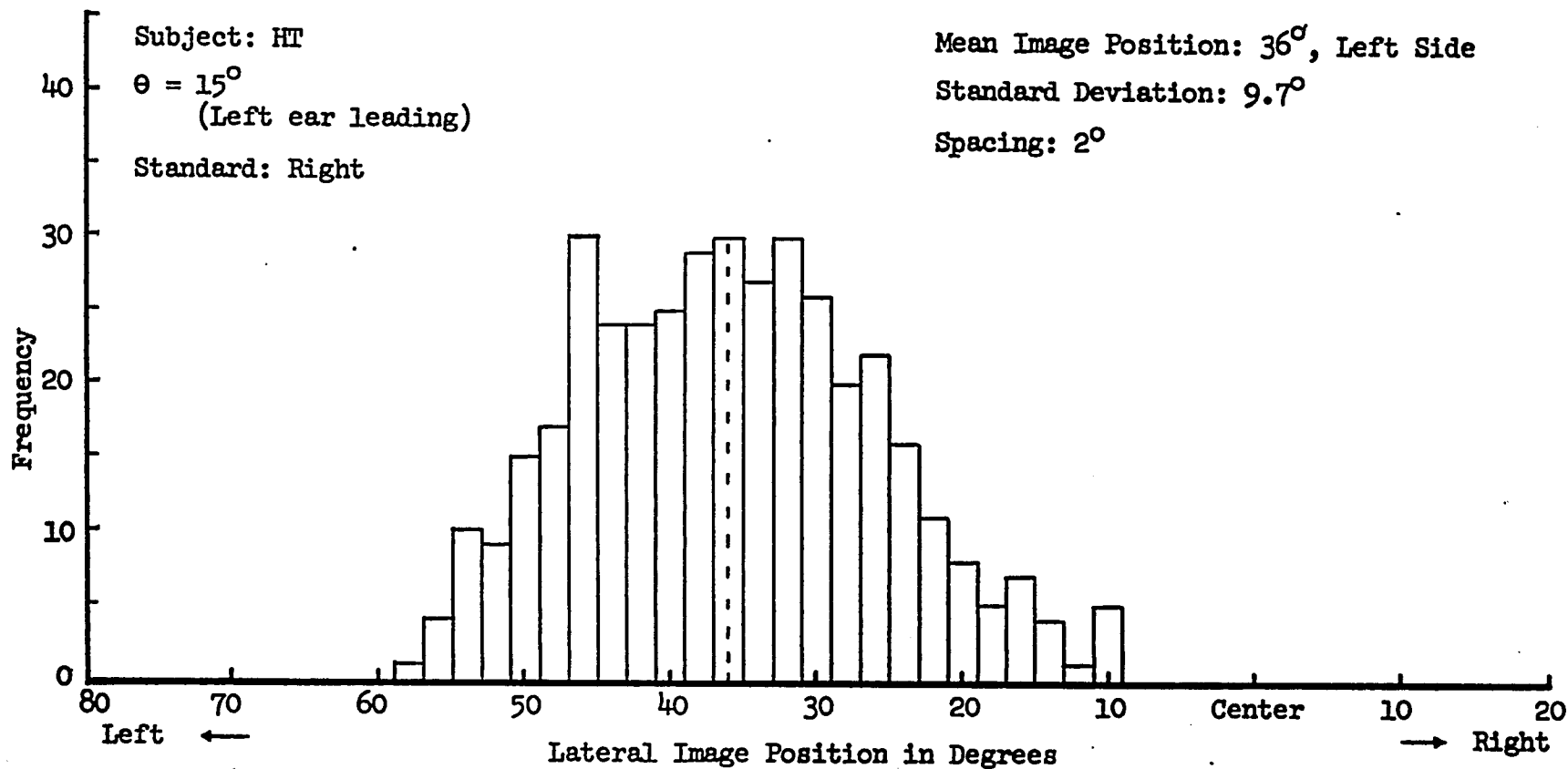


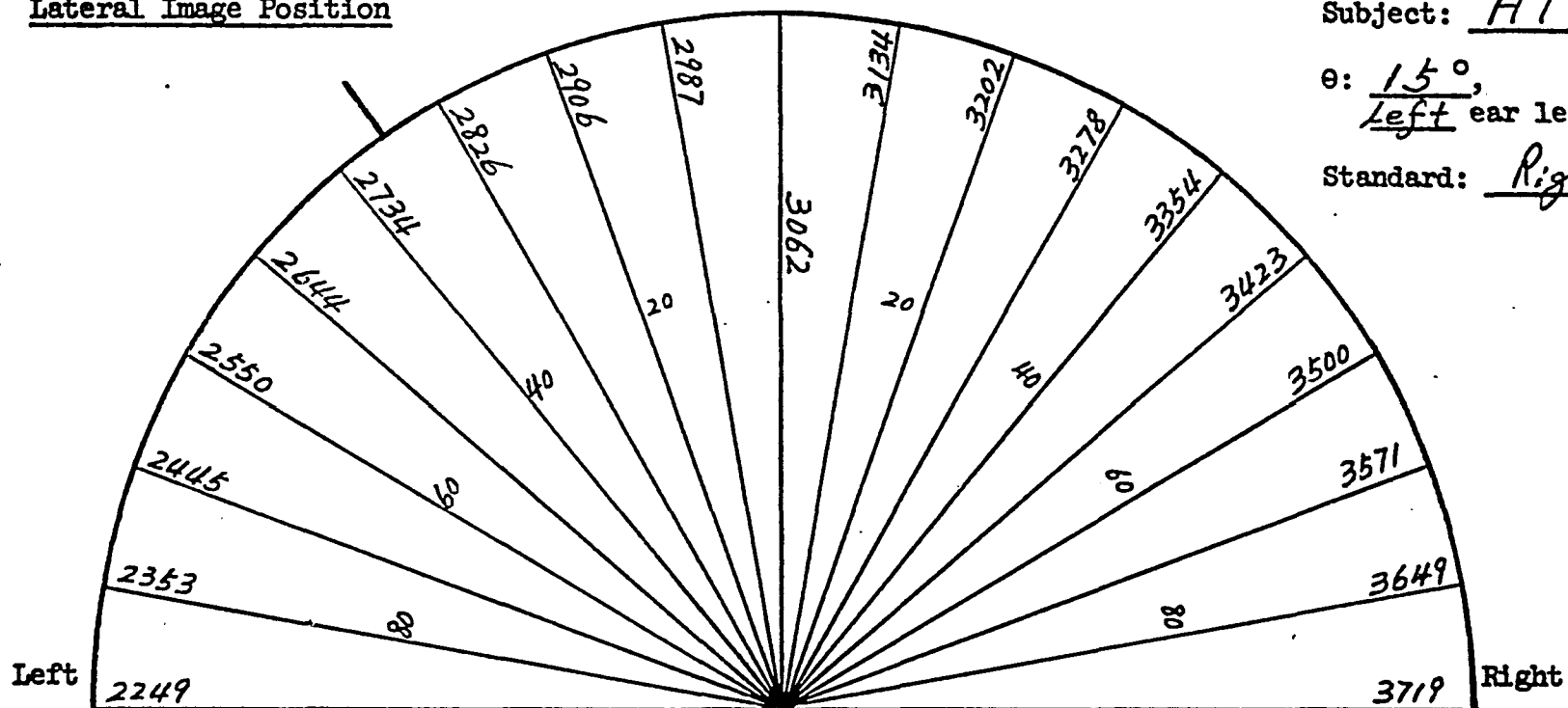
Figure 16. Sample of working sheet for data analysis. The informational items contained in the sheet are denoted as follows: Files - Name of data file on RK-05 disk; Interval of Histogram - Number of digital counts equivalent to a  $2^\circ$  spacing; Correction Figure - value for correction of standard deviation; Digit-Output Ref. - File name on RK-05 disk containing information which is presented in the second column of Table 1; Correlation - Correlation coefficient between four  $\theta_1$  values and corresponding digital outputs for mean positions; and Slope - Slope of the regression line for the above correlation.

Lateral Image Position

Subject: HT

$\theta$ : 15°,  
Left ear leading

Standard: Right



Date: 12/23/80.

Files: HYTLAT.169, 170, 171, 172.

Interval of Histogram: 18 ( $2^\circ$ ).

Correction Figure (for S.D.): 1.3°.

Signal: 250 Hz tone; 70 dB SPL;  
50 ms duration; 10 ms r/f.

$\theta$ : Phase Difference.

Digital-Output Ref.: MVM002.

Dig.-Output

	Mean	S.D.
$\theta_1 = 18$	2717	82.0
$\theta_2 = 16$	2755	92.4
$\theta_3 = 14$	2790	82.8
$\theta_4 = 12$	2836	106.9
$\theta = 15$	2772	90.3

Degrees

Mean	S.D.	
	Bef. Corret	Aft. Corret
42 L	9.1	9.0
37.5 L	10.0	10.0
34 L	9.0	8.9
28.5 L	13.4	13.3
36 L	9.8	9.7

Correlation = .9984.

Slope = 19.6000.

calibration reference data listed in Table 1. Referring to Figure 16, for example, the digital-output data representing  $\bar{P}$  and  $\sigma_p$  had values of 2772 and 90.3 counts, respectively, which were translated into  $36^\circ$  (left side) and  $9.8^\circ$ , correspondingly.

Finally, the position variance values derived from the experiment should be due to the listener's subjective process of lateralization of the binaural image, but conceivably could be also partially due to variability of mechanical adjustment and the mechanical position-digital transformation (when the listener tries to replicate a given pointer position again and again after recentering each time). The latter two forms of (undesirable) variability were carefully and repeatedly measured as described below. (This was a direct estimate of the subjects' ability to reset the pointer to several different positions, and was not the same as the mechanical linearity calibration previously described.) It was found that, in the final analysis, the variance adjustment required for removal of the effects of mechanical skill and equipment problems was quite small relative to the total variance, so that virtually all of the variance in the data was due to the subjective process of lateralization of the binaural image.

The procedure for obtaining subjects' mechanical variability values can be described briefly as follows. Six points in the semi-circular response space were selected, 3 on the left side

and 3 on the right side of the center, with absolute values of  $15^{\circ}$ ,  $45^{\circ}$ , and  $75^{\circ}$ . A short straight line (about one-half inch long) was marked at each of these 6 positions, extending about one inch above the semi-circular path traversed by the tip of the pointer. With no stimuli presented through the earphones, data were collected for the two listeners by using a procedure otherwise identical to that of the main experiment. The task for the listener was to move the pointer to one of the 6 positions trial by trial after recentering the pointer each time. Table 2 lists the results of these subject hand variance measurements, and it was used with linear interpolation as a reference to calibrate the corrections for all standard deviations. For example, in Figure 16 the final standard deviation was corrected to have a value of  $9.7^{\circ}$  from the original value of  $9.8^{\circ}$ .

Data for all 48 stimulus conditions and both subjects were treated using the same correction procedure, thus putting the results in final form for further analysis and discussion.

Table 2. Measurement of subjects' mechanical variability.

Data entries are standard deviations in degrees.

For a detailed explanation, see text.

Subject	Position in Degrees					
	Left Side			Right Side		
	75	45	15	15	45	75
HT	1.7	1.3	2.1	2.8	2.0	1.8
PT	1.3	1.9	1.8	2.1	2.3	1.7

### III. RESULTS

The reliability of the major features of the results is supported by the set of correlation coefficients for the various sets of four local values of phase shift and their corresponding mean values of computer-output for image position. These correlation data for the 48 nominal stimulus conditions and two listeners are listed in Table 3. Except for 5 values which are negative, most of the values are high positive correlations. Of the 96 correlation values, 66 are greater than +.800. It can be concluded that the listeners were able to locate four closely spaced binaural images in an appropriate lateral order corresponding to the different interaural phase shifts. In other words, listeners did respond to stimulus phase shifts properly and carefully; they did not simply put the pointer to an approximately closed region in lateral space on any trial. Thus, these correlation data ensure that the data collected in this study are highly reliable.

The major results of this study are the distributions representing each listener's subjective lateral image position judgements for the various nominal interaural phase differences (each determined by combining four subdistributions and appropriately corrected for bias, as described in the Methods Section). Table 4 presents means and standard deviations (both after correction), in degrees, of lateral image position

Table 3. Correlations between the four actual values of phase shift and the corresponding computer-output data for variations in nominal interaural phase difference.

		Nominal Interaural Phase Difference, $\theta$ (degrees)															
Standard	Subject	Left Ear Leading								Right Ear Leading							
		105	65	45	25	20	15	10	5	5	10	15	20	25	45	65	105
None	HT	.763	.940	.994	.963	.997	.965	.959	.992	.974	.845	.982	.958	.976	.972	.955	.949
	PT	.576	.881	.948	.844	.852	.930	.987	.979	.972	.971	.910	.894	.436	.750	.944	.418
Left	HT	.327	.955	.506	.934	.933	.465	.994	.975	.981	.949	.982	.992	.832	.932	.994	.303
	PT	<u>.112</u>	<u>.034</u>	.974	.934	.411	.870	.582	.944	.893	.984	.995	.956	.866	.998	.121	<u>.355</u>
Right	HT	.777	.761	.962	.972	.663	.998	.995	.967	.994	.909	.997	.875	.947	.824	.418	.391
	PT	.858	.954	.161	.561	.493	.180	.966	.947	.684	.978	<u>.141</u>	.837	.629	<u>.054</u>	.633	.744

Data underlined indicate negative correlations.

Table 4. Means and standard deviations (S.D.), in degrees, of lateral image position distributions for variations in interaural phase difference, in degrees, of 250-Hz binaural tone bursts without standard. Letter L or R following each mean value indicates image is located on either the left side or the right side of the center.

		Interaural Phase Difference, $\theta$ (Left Ear Leading)							
		105	65	45	25	20	15	10	5
HT	Mean	45.4-L	14.0-L	5.9-L	15.8-L	13.1-L	12.6-L	14.2-L	10.4-L
	S.D.	20.4	10.3	4.3	6.0	5.8	5.2	6.6	4.5
PT	Mean	79.5-L	39.5-L	19.1-L	28.5-L	9.7-L	2.4-L	14.6-L	3.1-L
	S.D.	6.8	11.1	6.3	13.4	4.0	6.9	7.3	5.0

		Interaural Phase Difference, $\theta$ (Right Ear Leading)							
		5	10	15	20	25	45	65	105
HT	Mean	8.5-R	9.7-R	9.2-R	11.3-R	17.8-R	19.3-R	32.5-R	52.3-R
	S.D.	6.0	3.8	4.2	5.0	6.6	7.5	8.4	13.7
PT	Mean	1.0-R	2.1-R	3.8-R	11.2-R	3.3-R	36.5-R	28.2-R	45.1-R
	S.D.	7.6	5.3	5.4	4.9	3.8	13.4	8.2	13.7

distributions for the 16 nominal interaural phase differences,  $\theta$  (in degrees), for both listeners under the condition without a standard. Results for the conditions with the left standard and the right standard are listed, in similar form, in Table 5 and Table 6, respectively. Note that, in these three tables, the letter L or R following each mean value indicates that the listener's subjective lateral image is located accordingly on either the left side or the right side of the subjective center.

Results listed in Tables 4, 5, and 6 are then represented by plotting the mean values of lateral image position ( $\bar{P}$ ), in degrees, as a function of the interaural phase difference of the binaural signal ( $\theta$ ), in degrees. The size of the standard deviation ( $\sigma_p$ ), in degrees, for each position distribution is indicated by a vertical bar around the mean. Figures 17 and 18 depict the data of the two listeners (HT and PT, respectively) for the condition without standard. The corresponding data of the two listeners and for the conditions with the left standard and the right standard are plotted in Figures 19, 20, 21, and 22, separately.

For the condition with no standard employed in the first interval, the mean value of subjective lateral image position is directly related to the interaural phase difference,  $\theta$ . In Figures 17 and 18, both subjects show a similar tendency, such that setting  $\theta$  values to  $\pm 105^\circ$  yields a  $\bar{P}$  of the order of  $\pm 40^\circ$

Table 5. Means and standard deviations (S.D.), in degrees, of lateral image position distributions for variations in interaural phase difference, in degrees, of 250-Hz binaural tone bursts with left standard. Letter L or R following each mean value indicates image is located on either the left side or the right side of the center.

		Interaural Phase Difference, $\theta$ (Left Ear Leading)							
		105	65	45	25	20	15	10	5
HT	Mean	27.0-R	3.8-R	14.3-R	10.1-R	11.6-R	15.3-R	7.6-R	1.9-R
	S.D.	9.9	6.3	4.4	2.9	4.5	6.7	5.3	4.2
PT	Mean	2.3-L	11.9-R	3.7-L	1.6-L	19.7-R	18.8-R	6.1-R	25.0-R
	S.D.	7.2	11.8	6.7	7.2	14.0	15.4	7.2	8.7

		Interaural Phase Difference, $\theta$ (Right Ear Leading)							
		5	10	15	20	25	45	65	105
HT	Mean	14.3-R	15.7-R	40.6-R	45.5-R	33.6-R	27.6-R	60.8-R	85.6-R
	S.D.	4.8	7.2	12.7	13.2	11.3	7.8	13.1	3.1
PT	Mean	31.2-R	18.5-R	26.8-R	18.1-R	23.7-R	61.1-R	28.3-R	87.0-R
	S.D.	10.9	10.2	7.1	7.0	8.0	12.4	8.4	5.4

Table 6. Means and standard deviations (S.D.), in degrees, of lateral image position distributions for variations in interaural phase difference, in degrees, of 250-Hz binaural tone bursts with right standard. Letter L or R following each mean value indicates image is located on either the left side or the right side of the center.

		Interaural Phase Difference, $\theta$ (Left Ear Leading)							
		105	65	45	25	20	15	10	5
HT	Mean	69.9-L	66.7-L	64.1-L	54.5-L	50.9-L	35.9-L	17.3-L	13.0-L
	S.D.	8.5	9.4	8.1	9.5	12.1	9.7	6.9	5.1
PT	Mean	84.0-L	62.0-L	61.8-L	41.9-L	37.7-L	33.6-L	21.1-L	25.6-L
	S.D.	2.3	9.1	8.8	11.0	10.5	8.1	7.9	7.4

		Interaural Phase Difference, $\theta$ (Right Ear Leading)							
		5	10	15	20	25	45	65	105
HT	Mean	9.6-L	2.1-L	18.9-L	26.4-L	10.9-L	1.9-R	5.3-R	13.2-R
	S.D.	4.7	3.4	6.6	10.4	4.8	3.3	2.4	12.3
PT	Mean	13.8-L	5.1-L	31.8-L	30.7-L	43.9-L	13.0-L	6.9-R	5.6-R
	S.D.	8.5	6.3	7.6	7.6	8.2	4.6	3.0	7.3

Figure 17. Mean lateral image position ( $\bar{P}$ ), in degrees, as a function of interaural phase difference ( $\theta$ ), in degrees, with either the left ear leading in phase or the right ear leading in phase. The size of the standard deviation, in degrees, for each position distribution is indicated by a vertical bar. Data points are for subject IIT and the condition without standard.

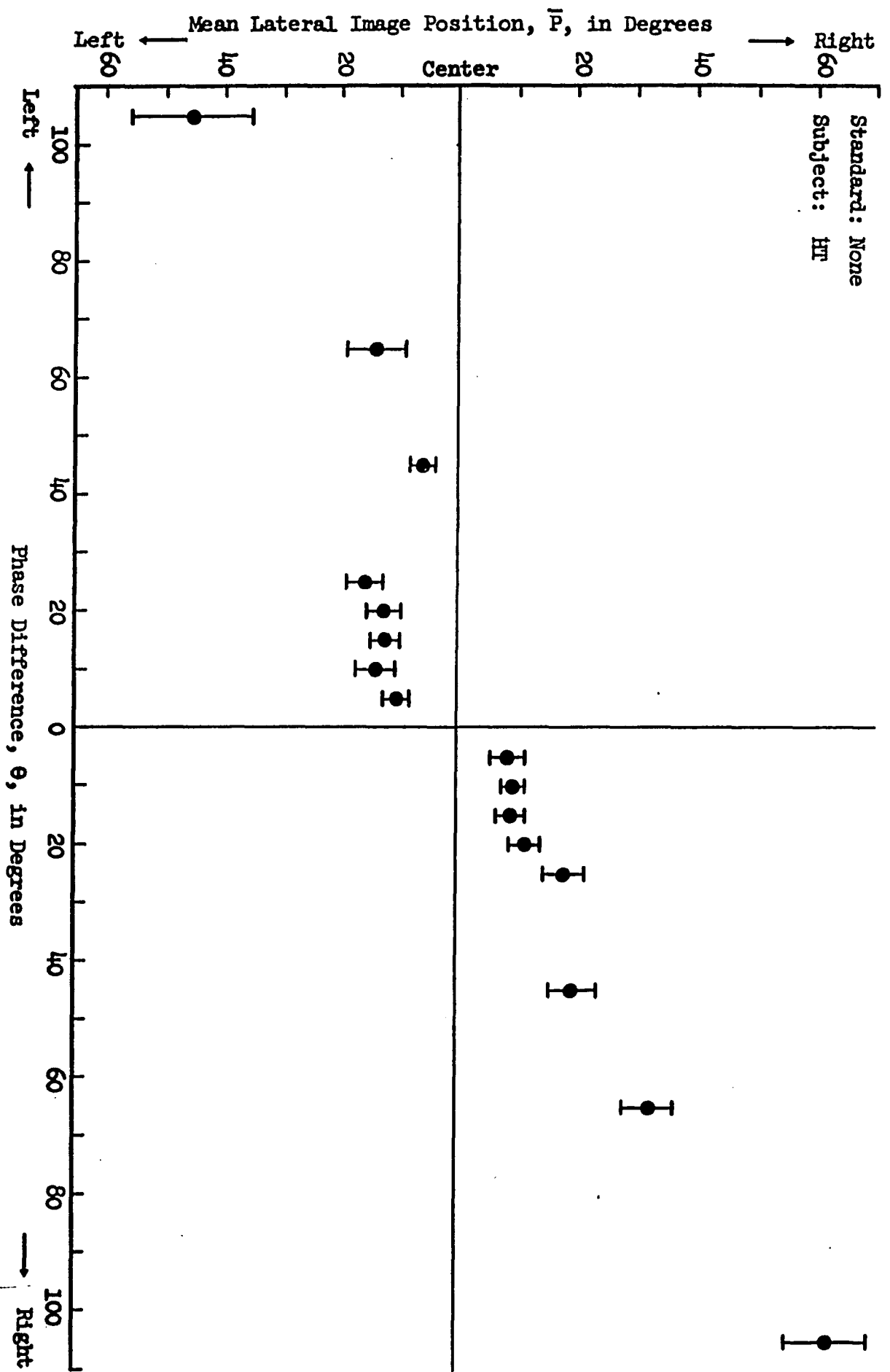


Figure 18. Mean lateral image position ( $\bar{P}$ ), in degrees, as a function of interaural phase difference ( $\theta$ ), in degrees, with either the left ear leading in phase or the right ear leading in phase. The size of the standard deviation, in degrees, for each position distribution is indicated by a vertical bar. Data points are for subject PT and the condition without standard.

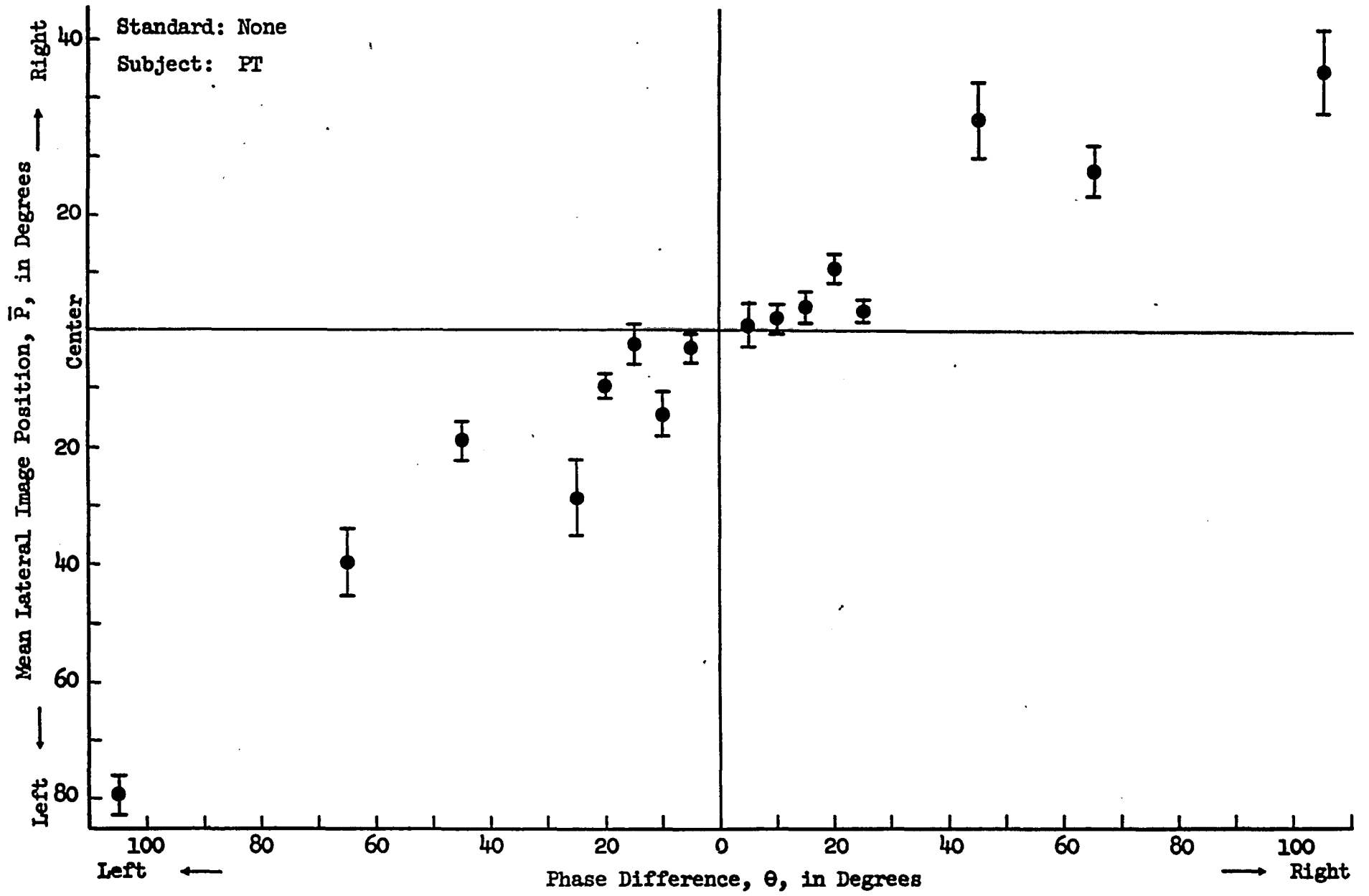


Figure 19. Mean lateral image position ( $\bar{P}$ ), in degrees, as a function of interaural phase difference ( $\theta$ ), in degrees, with either the left ear leading in phase or the right ear leading in phase. The size of the standard deviation, in degrees, for each position distribution is indicated by a vertical bar. Data points are for subject HT and the condition with left standard.

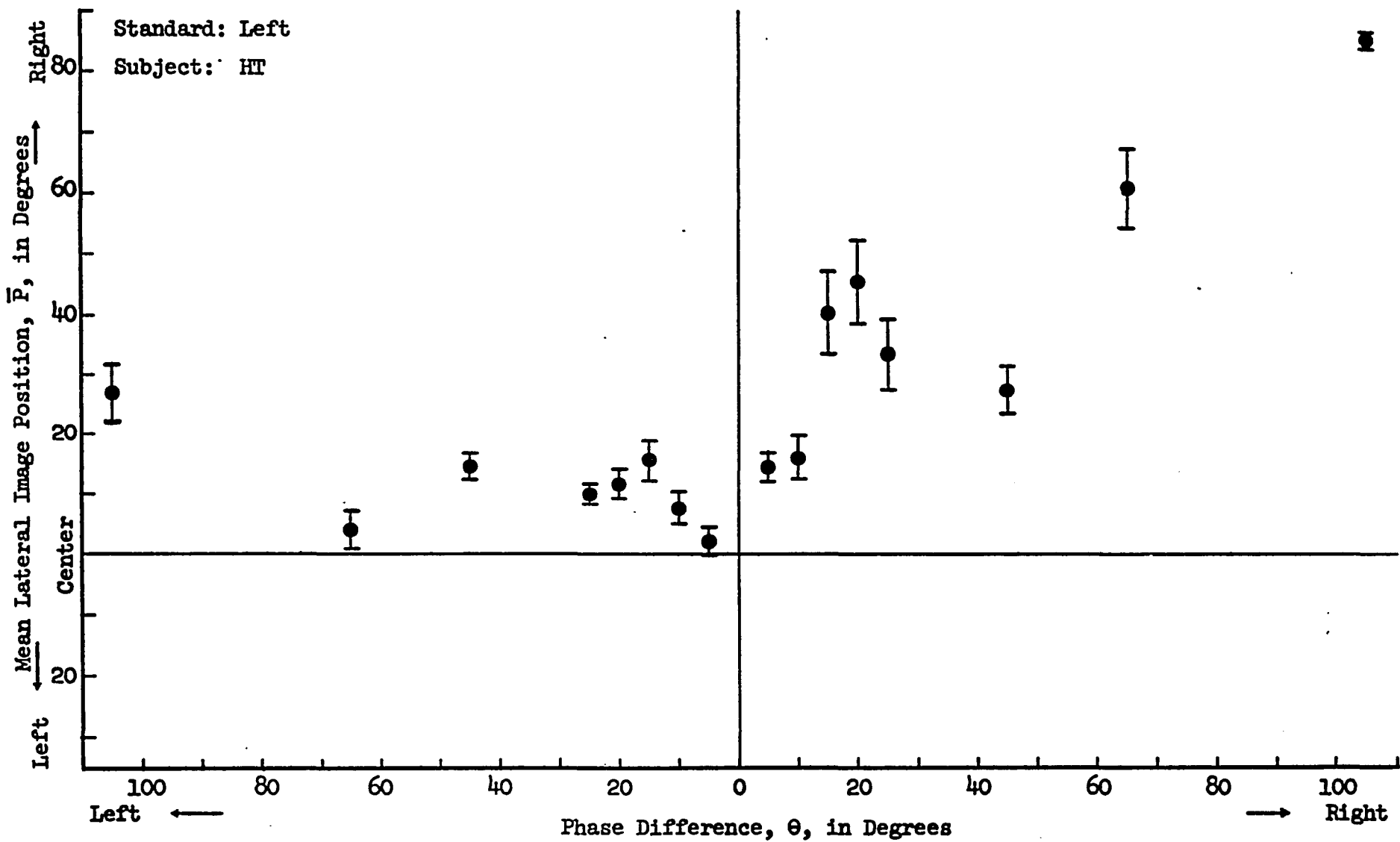


Figure 20. Mean lateral image position ( $\bar{P}$ ), in degrees, as a function of interaural phase difference ( $\theta$ ), in degrees, with either the left ear leading in phase or the right ear leading in phase. The size of the standard deviation, in degrees, for each position distribution is indicated by a vertical bar. Data points are for subject PT and the condition with left standard.

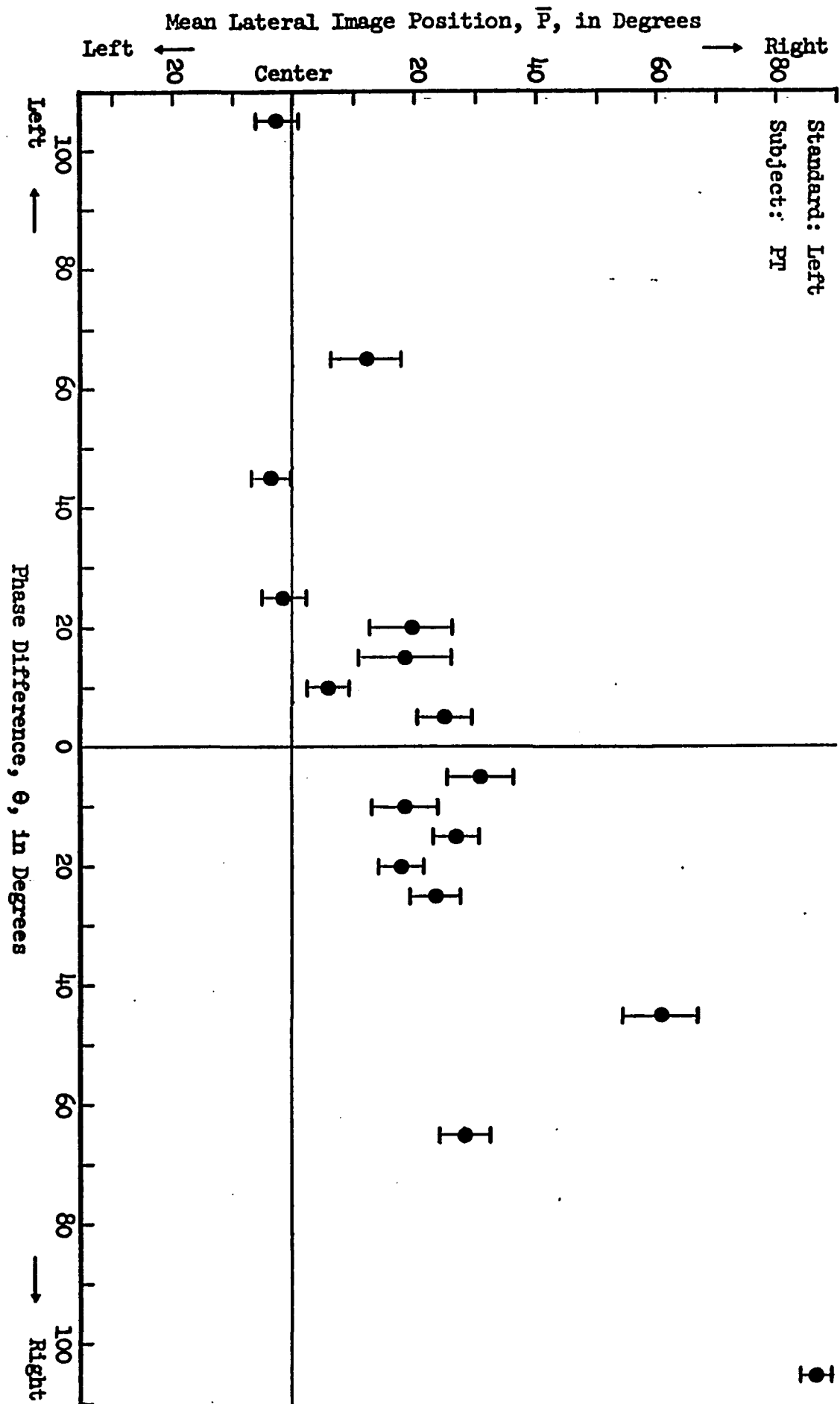


Figure 21. Mean lateral image position ( $\bar{P}$ ), in degrees, as a function of interaural phase difference ( $\theta$ ), in degrees, with either the left ear leading in phase or the right ear leading in phase. The size of the standard deviation, in degrees, for each position distribution is indicated by a vertical bar. Data points are for subject HT and the condition with right standard.

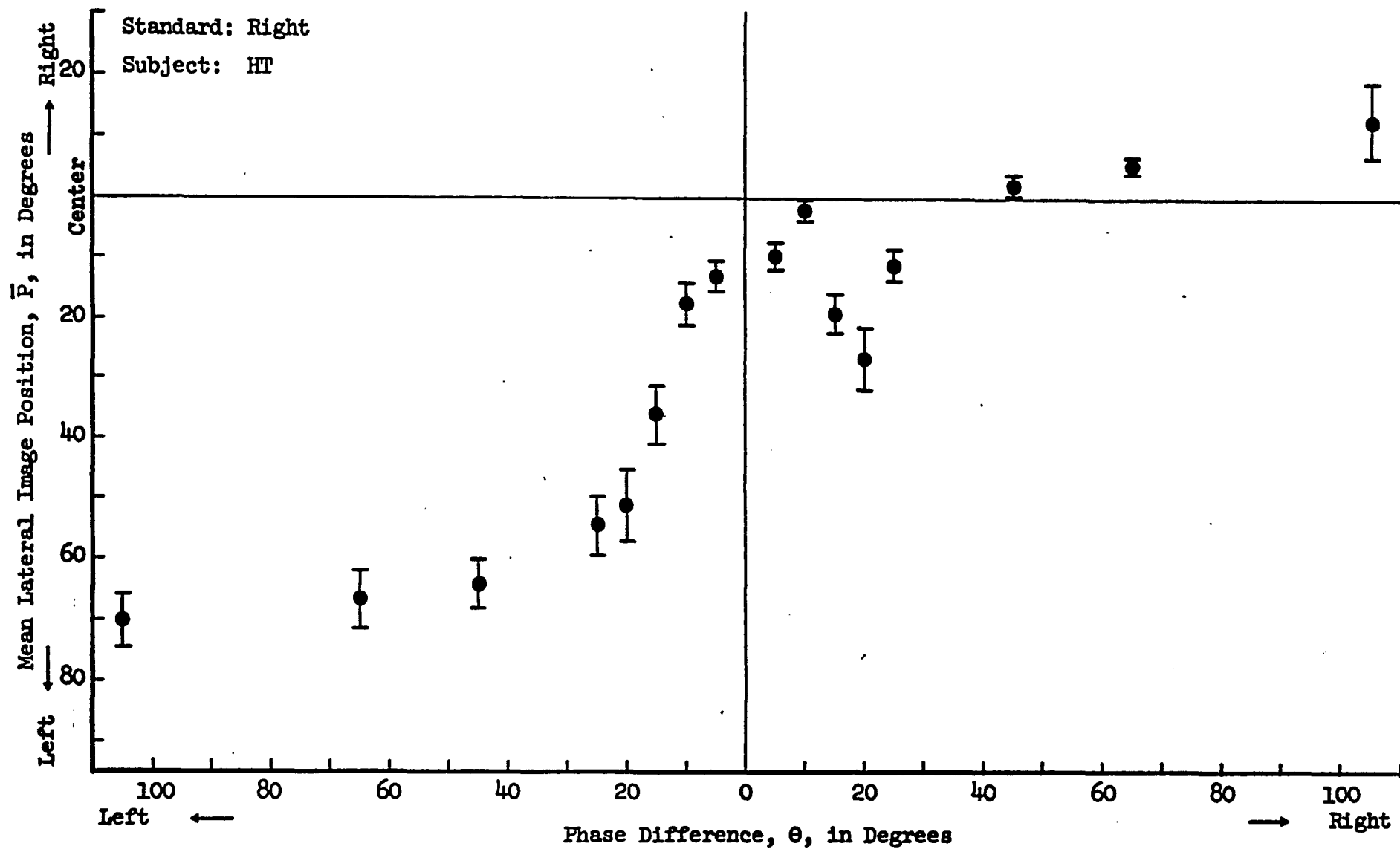
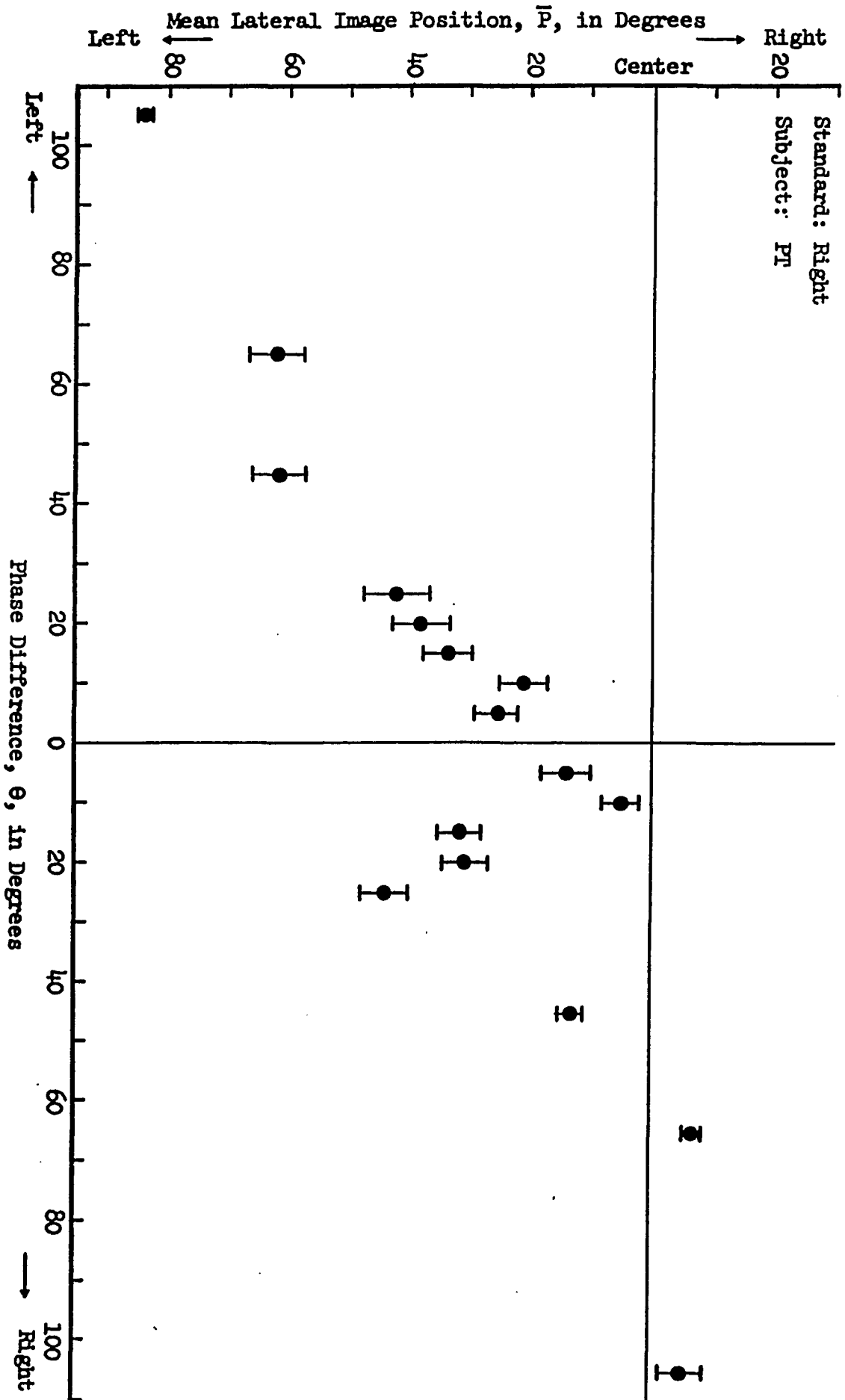


Figure 22. Mean lateral image position ( $\bar{P}$ ), in degrees, as a function of interaural phase difference ( $\theta$ ), in degrees, with either the left ear leading in phase or the right ear leading in phase. The size of the standard deviation, in degrees, for each position distribution is indicated by a vertical bar. Data points are for subject PT and the condition with right standard.



to  $\pm 80^\circ$  from the subjective center, while  $\theta$  near  $0^\circ$  yields a  $\bar{P}$  close to subjective center and displaced in the expected direction.

The introduction of a monaural standard stimulus, which itself is fully lateralized either at the left ear or at the right ear, produced a huge shift in the entire set of subjective lateral image position judgements away from the ear which received the standard stimulus. As shown in Figure 19, when the left standard was introduced, the entire set of image positions of subject HT locates in the range from about  $5^\circ$  to about  $85^\circ$  to the right side of the subjective center. This includes the images for the 8 interaural phase differences where the left ear was leading in phase. By contrast, for the condition with no standard, the range is from about  $45^\circ$  to the left side to about  $50^\circ$  to the right side of the center, with 8 image positions located at each side in an appropriate order. For subject PT, in Figure 20, the entire set of image positions falls in the range from about  $2^\circ$  to the left side to about  $85^\circ$  to the right side of the center, with only 3 image positions located at the left. Again, looking at the condition with no standard, the range is about from  $80^\circ$  to the left side to  $45^\circ$  to the right side of the center. When the right standard was introduced, the shift of the image position was reversed, with movement to the left side of the center. For subject HT (Figure 21), the set of image positions given a right standard

locates in a range from about  $13^{\circ}$  to the right side to about  $70^{\circ}$  to the left side with only 3 images located to the right. Similarly, for subject PT (Figure 22), the range of image positions locates from about  $7^{\circ}$  to the right side to about  $84^{\circ}$  to the left side with only 2 images located to the right side of the center. In summary, the shift with either standard is so large that only 8 of the 64 subjective image positions locate on the standard's side of the midline. In other words, the monaural standard stimulus, even though it occurred 500 msec before the binaural test stimulus, had a very strong effect on listeners' judgements of subjective lateral image position.

Further examination of the results reveals the very interesting fact that the variance of lateral position judgements is a function of mean lateral image position ( $\bar{P}$ ), per se. It is independent of stimulus parameters such as interaural phase difference,  $\theta$ , and standard condition. Both listeners in this study had similar results. For the condition without standard (see Figures 17 and 18), the standard deviation,  $\sigma_p$ , is minimal and has values of the order of  $4^{\circ}$  to  $5^{\circ}$  when image position locates near subjective center (on either side). It increases to a maximum of about three to four times that magnitude when image position locates near about  $40^{\circ}$  or so to the left or right of the center, and then decreases to a small value of about  $7^{\circ}$  when image position moves to about  $80^{\circ}$  (on either side) from the center. As mentioned in the previous paragraph, the monaural

standard stimulus (either at the left or the right ear) produced a dramatic effect such that the entire set of subjective lateral position distributions was pushed away from the ear which received the standard stimulus. However, it was also (surprisingly) found that the value of the standard deviation was changed when the mean of the distribution was shifted by the existence of the standard. For example, for the condition without standard and the test signal having a  $20^\circ$  interaural phase difference with the right ear leading in phase, the image position of subject HT locates at about  $13^\circ$  to the right side of the center and the standard deviation has a value of only about  $5^\circ$ . However, with the right standard introduced, not only is the image position shifted to about  $26^\circ$  to the left side of the center, but the standard deviation is also changed to yield a value of about  $11^\circ$ .

After carefully examining Figures 19 to 22, it is clear that the change in the standard deviation ( $\sigma_p$ ) of the subjective lateral image distribution associated with the shifting of the mean ( $\bar{P}$ ) produced by the standard is related only to the mean, and is independent of the interaural phase difference ( $\theta$ ) of the binaural stimulus. For the condition with either the left standard or the right standard, the standard deviation has the minimal value of about  $2^\circ$  to  $3^\circ$  when listeners locate their subjective lateral image positions near the subjective center (on either side). It increases to a maximum of about  $13^\circ$  to  $14^\circ$

with image position located at about  $40^\circ$  to  $50^\circ$  to the left or right of the center, regardless of the value of  $\theta$ , and then decreases to the minimum again for the limiting placements of image position of about  $85^\circ$  to the left side or the right side of the center.

It is now useful to remove all information concerning the signal interaural phase difference,  $\theta$ , from the data displays. The data for subject HT (in Figures 17, 19, and 21) are transformed into Figure 23 by plotting the standard deviation ( $\sigma_p$ ) as a function of the mean value of lateral image position ( $\bar{P}$ ) for each lateral position distribution. Data for subject PT (in Figures 18, 20, and 22) are also replotted in the same way in Figure 24. These two figures include the data for all three conditions of standard, as indicated in each of three separate panels. For alternative useful representations, the data are also replotted, by using the same format, with the standard deviation as a function of the mean of each lateral position distribution, first for each listener collapsed across the three conditions of standard, and then for each condition of standard collapsed across the two listeners. Figures 25 and 26 depict the results collapsed over three conditions for listeners HT and PT, respectively. Figures 27, 28, and 29 depict the results collapsed across the two listeners for the conditions without standard, with left standard, and with right standard, respectively.

Figure 23. Standard deviation ( $\sigma_p$ ), in degrees, as a function of mean lateral image position ( $\bar{P}$ ), in degrees, for subject HT. Data points include all three conditions of standard, as indicated in each panel.

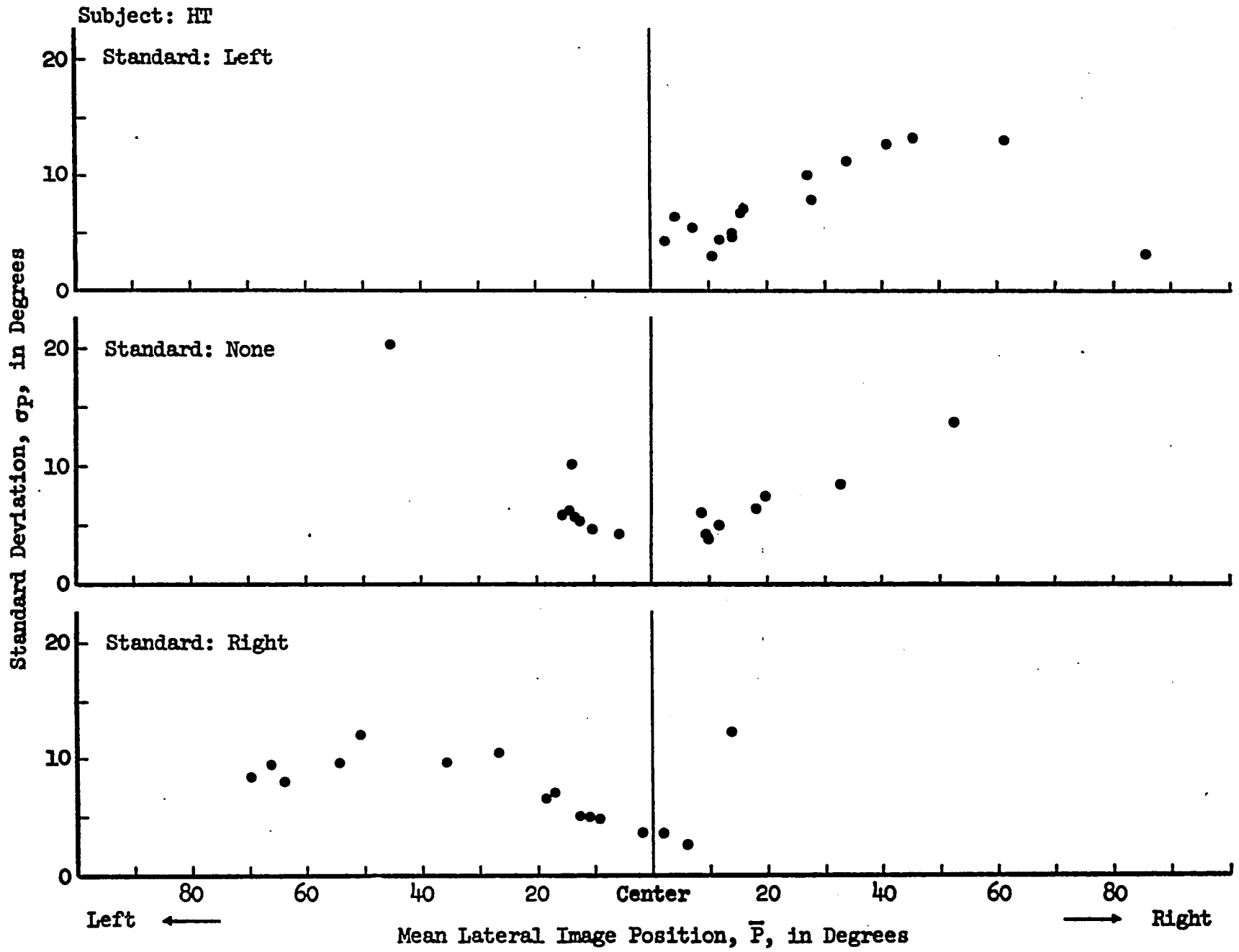


Figure 24. Standard deviation ( $\sigma_p$ ), in degrees, as a function of mean lateral image position ( $\bar{P}$ ), in degrees, for subject PT. Data points include all three conditions of standard, as indicated in each panel.

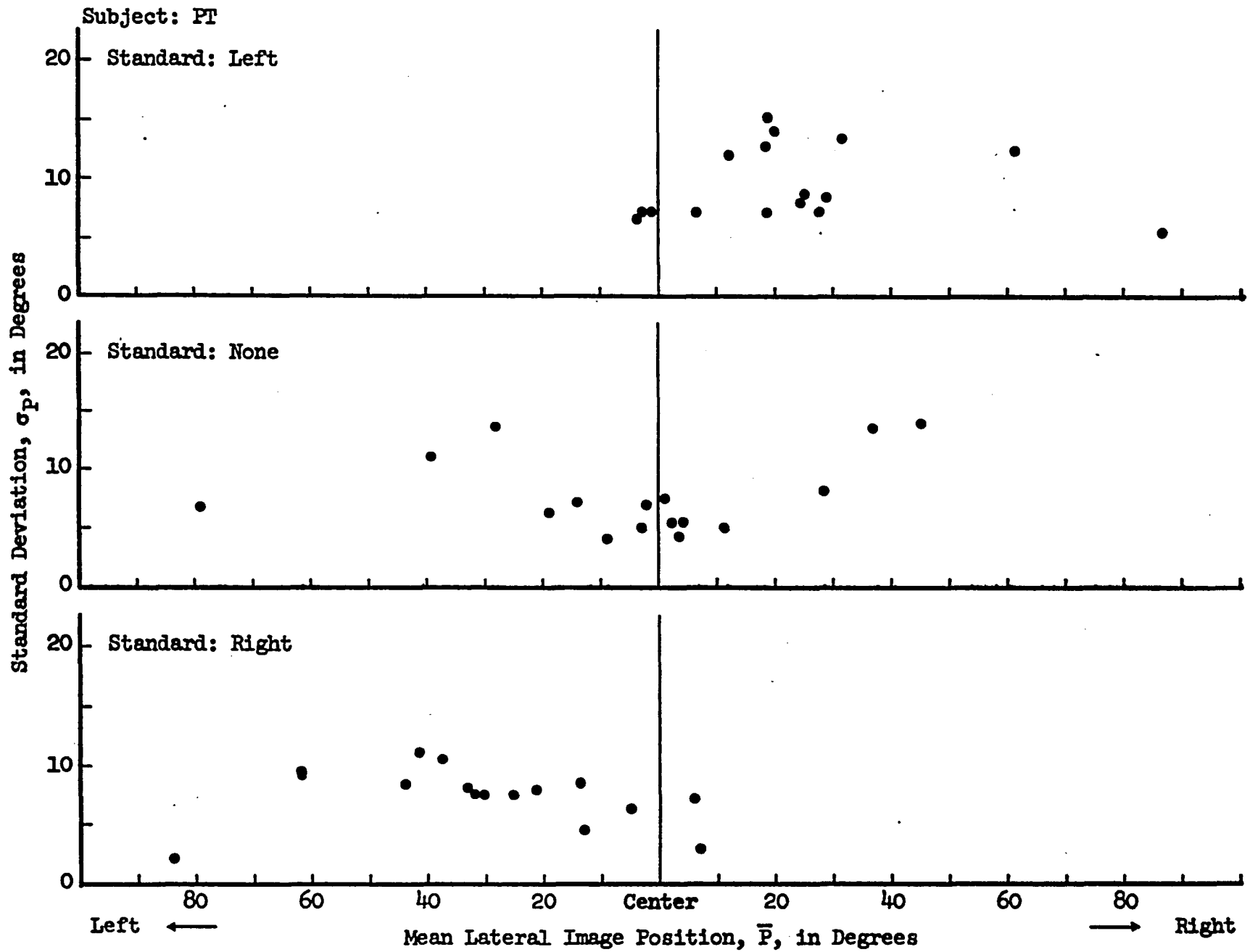


Figure 25. Standard deviation ( $\sigma_p$ ), in degrees, as a function of mean lateral image position ( $\bar{P}$ ), in degrees, for subject MT. Data points are replotted from Figure 23 by collapsing across three conditions of standard.

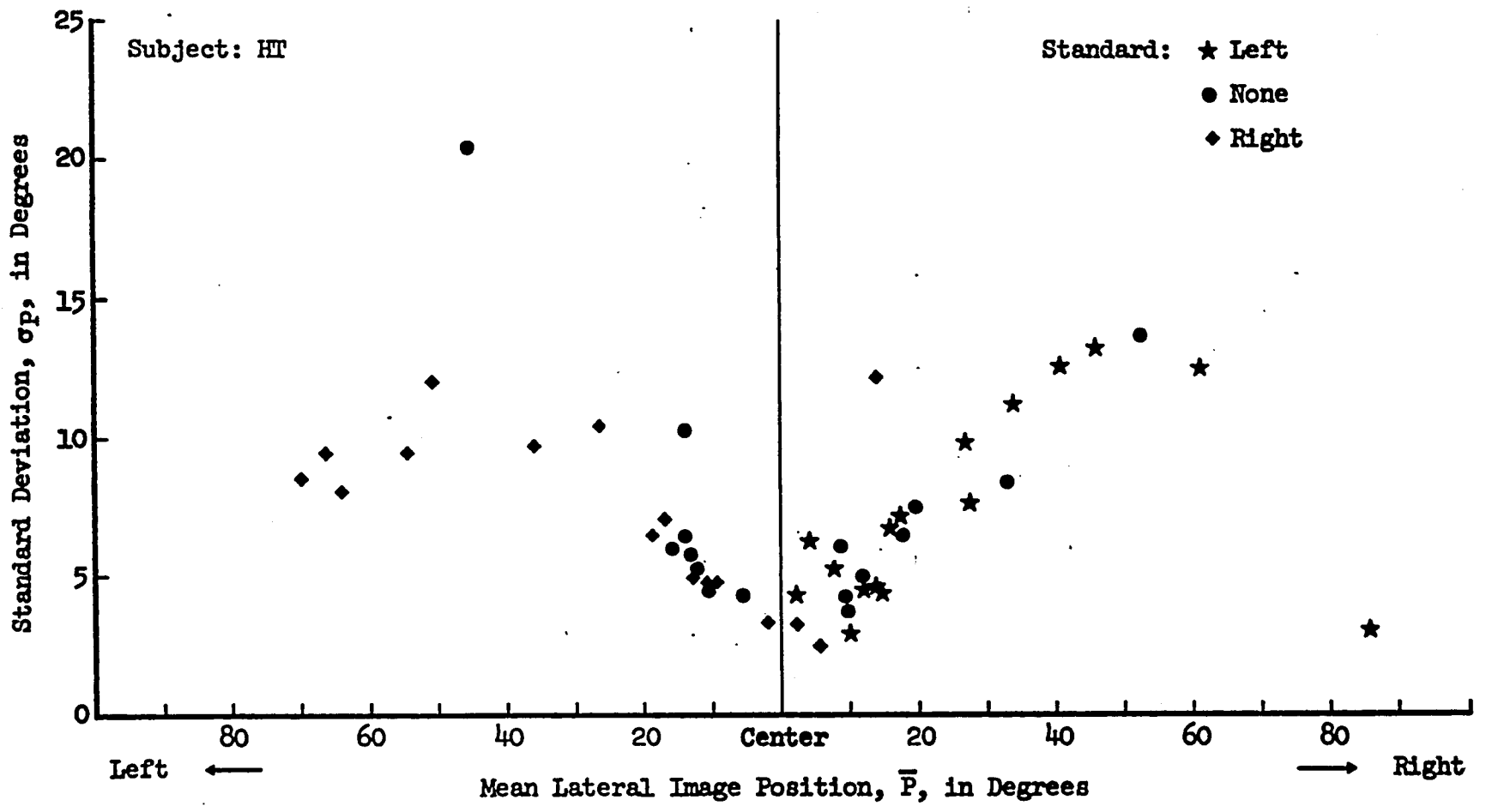


Figure 26. Standard deviation ( $\sigma_p$ ), in degrees, as a function of mean lateral image position ( $\bar{P}$ ), in degrees, for subject PT. Data points are replotted from Figure 24 by collapsing across three conditions of standard.



Figure 27. Standard deviation ( $\sigma_p$ ), in degrees, as a function of mean lateral image position ( $\bar{P}$ ), in degrees, for the condition without standard. Data points are replotted by collapsing across two subjects.

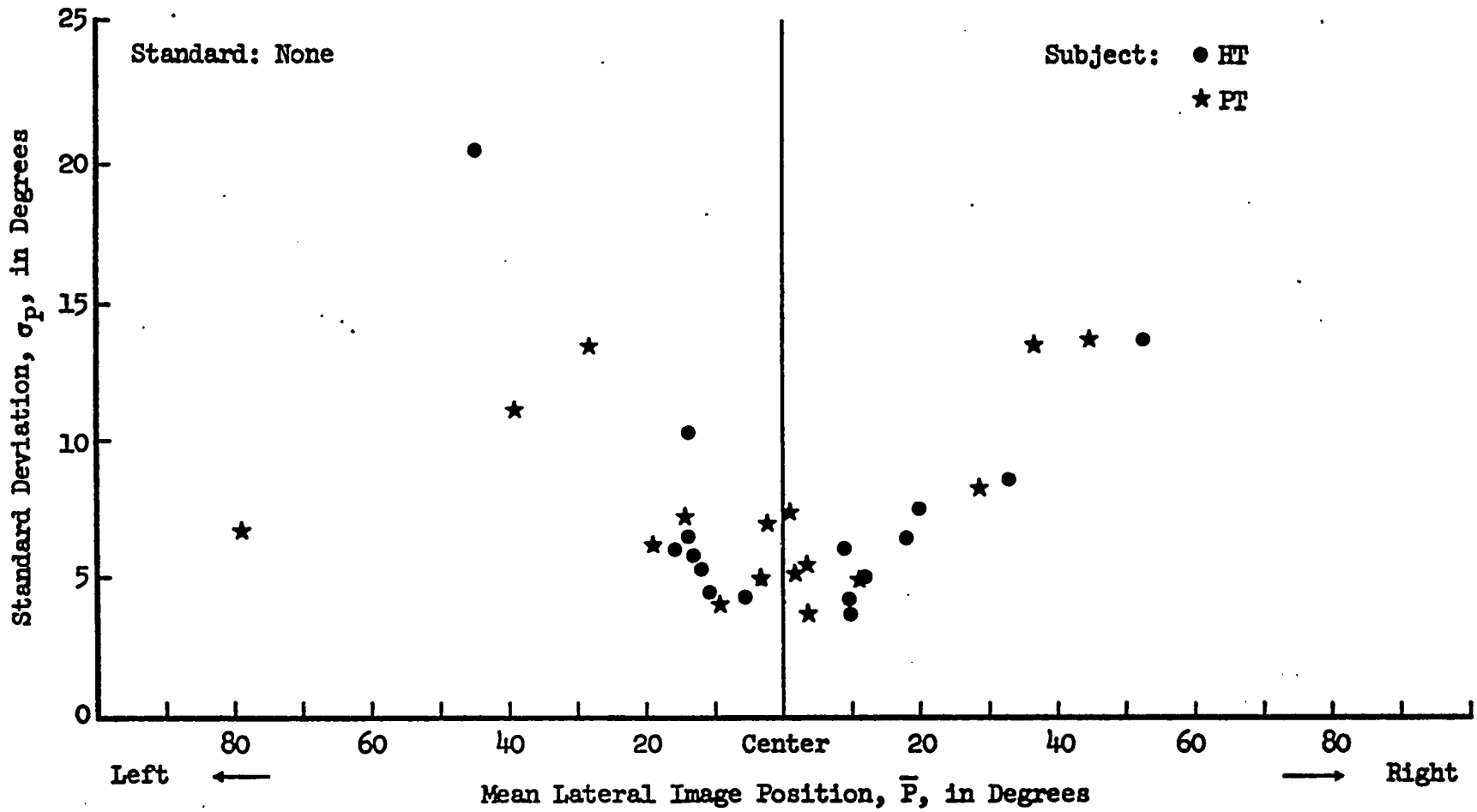


Figure 28. Standard deviation ( $\sigma_p$ ), in degrees, as a function of mean lateral image position ( $\bar{P}$ ), in degrees, for the condition with left standard. Data points are replotted by collapsing across two subjects.

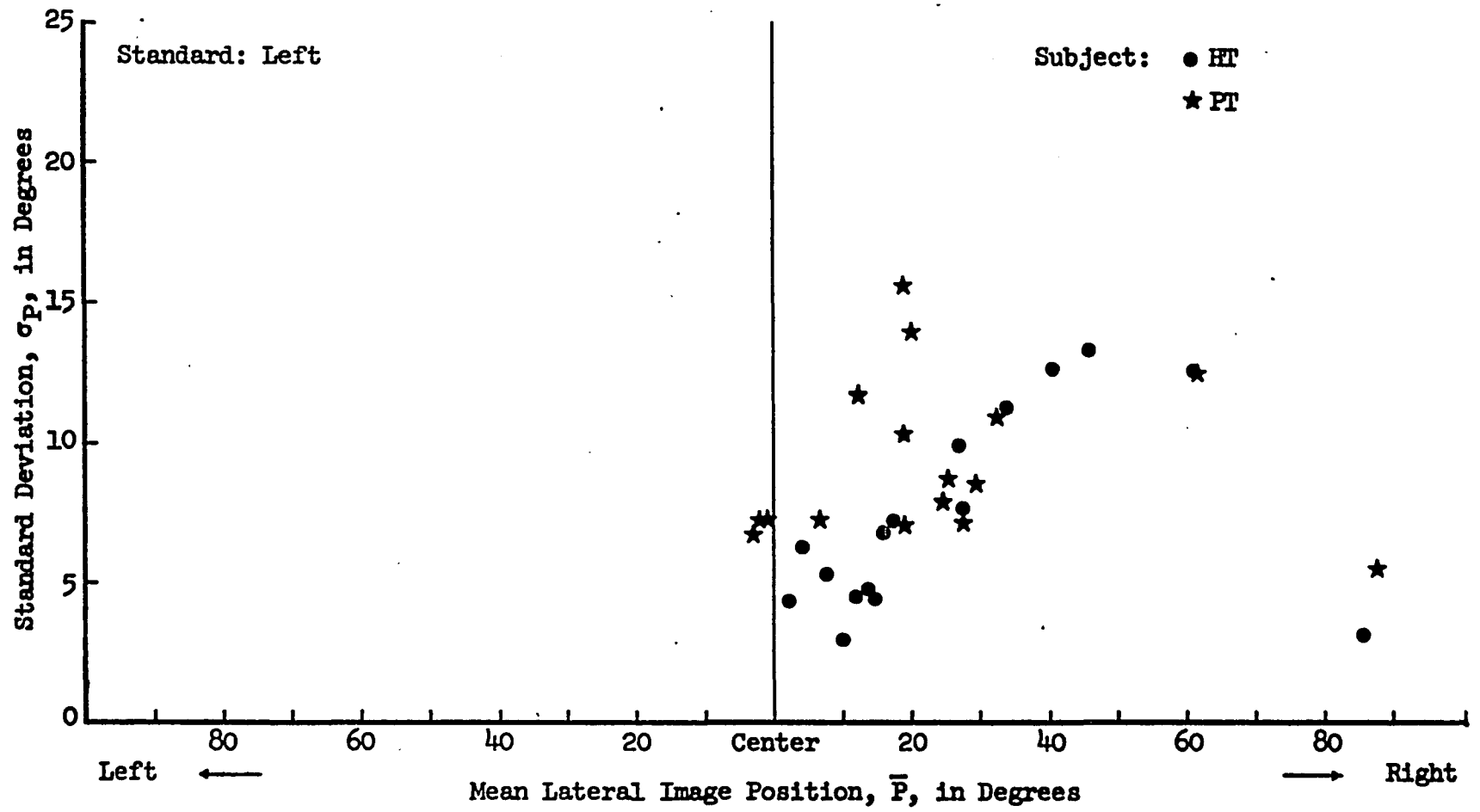
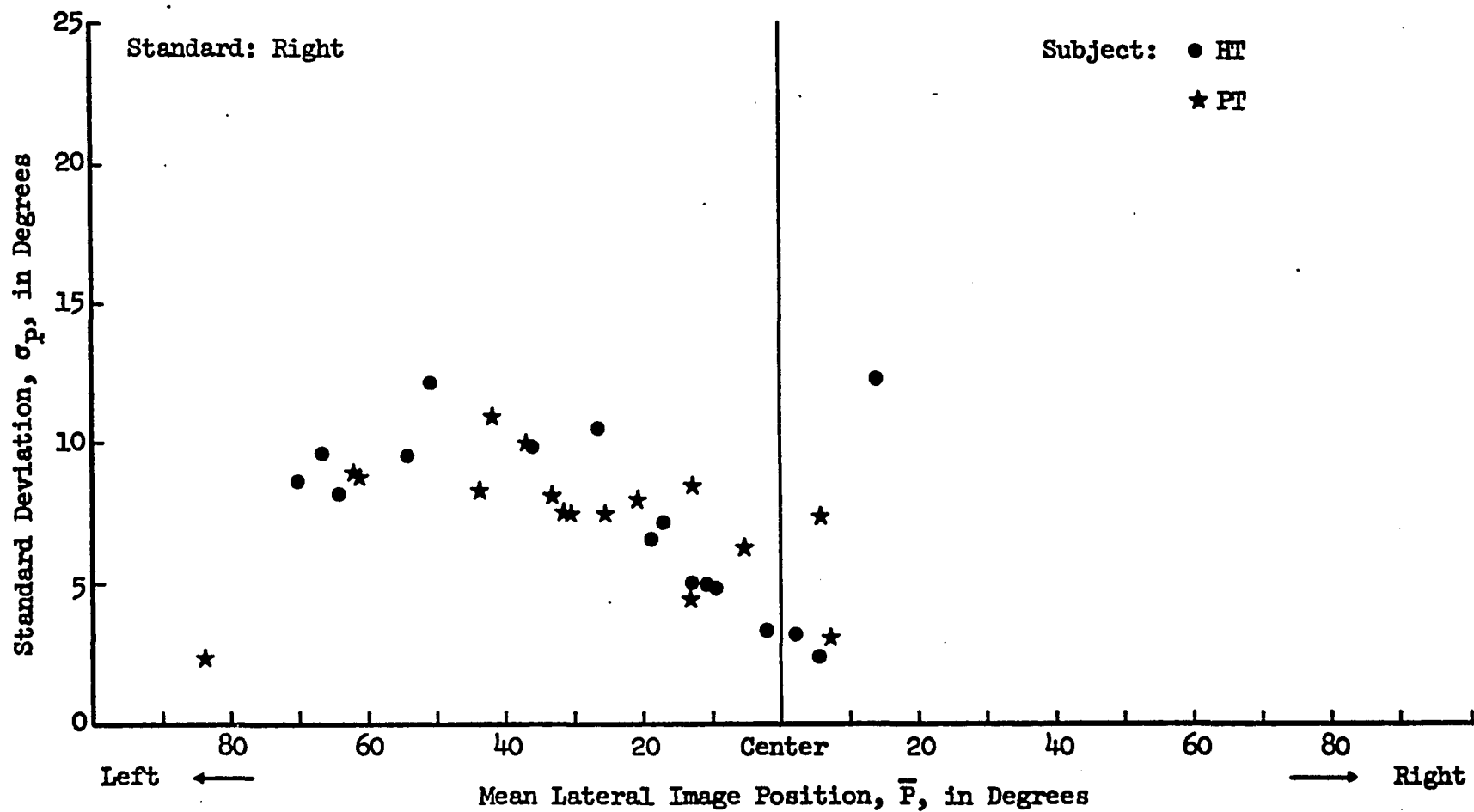


Figure 29. Standard deviation ( $\sigma_p$ ), in degrees, as a function of mean lateral image position ( $\bar{P}$ ), in degrees, for the condition with right standard. Data points are replotted by collapsing across two subjects.



In Figures 25 and 26, it is clear that, for both listeners, the standard deviation ( $\sigma_p$ ) is simply a function of mean subjective lateral image position ( $\bar{P}$ ). Except for a few data points, the function is very smooth and has symmetry with respect to subjective center. The standard deviation has the minimal value of about  $5^\circ$  when the image locates near subjective center (on either side). It starts to increase smoothly when the image moves laterally away from the center and reaches a maximum of about  $15^\circ$  as the image locates at about  $40^\circ$  to  $50^\circ$  off the center. Finally, it decreases smoothly again and reaches another minimal value of about  $5^\circ$  when the image locates at an apparent outer limit of about  $85^\circ$  to either side of the center. The effect of the introduction of a monaural standard is also clearly shown in Figures 27, 28, and 29. In the condition without standard, data points for  $\sigma_p$  fall symmetrically on either side of subjective center (and that is in accordance with the interaural phase differences). However, when a monaural standard (at either the left ear or the right ear) is introduced, almost all the  $\sigma_p$  data points that result are for positions away from the side that receives the standard. Note that, regardless of the way position judgements are shifted, the standard deviation maintains its direct relation to mean subjective lateral image position and is independent of the condition of the standard.

Because the performances of the two listeners were similar to each other, it is appropriate to average their results for

each stimulus condition, such as interaural phase difference or standard condition. Table 7 lists the averaged results of means and standard deviations for all three conditions of standard. Again, these averaged results are then represented by plotting the mean of the lateral image position ( $\bar{P}$ ) as a function of interaural phase difference ( $\theta$ ), along with the size of the standard deviation ( $\sigma_P$ ) indicated by a vertical bar, in Figures 30, 31, and 32 for the conditions without standard, with the left standard, and with the right standard, respectively. The data points in Figures 30, 31, and 32 are then replotted by suppressing  $\theta$ , with the standard deviation ( $\sigma_P$ ) as a function of mean subjective lateral image position ( $\bar{P}$ ) in Figure 33. All these averaged data show trends similar to the individual data.

The major features of the results have now been summarized. This study concerns measurement of the lateral positions of acoustic images produced by binaural tonal signals with different interaural phase differences, and includes the effects of introducing a monaural standard stimulus. It focuses on local statistical properties across the span of the listener's subjective lateralization space. Two major findings from this study seem especially important with regard to binaural lateralization. (1) The location of the listener's subjective lateral image position is clearly influenced by a temporally distant reference signal that occurs one-half second before the binaural test signal. The introduction of a monaural standard

Table 7. Means and standard deviations (S.D.), in degrees, of lateral image position distributions for variations in interaural phase difference, in degrees, of 250-Hz binaural tone bursts. Data are averages over two listeners. Letter L or R following each mean value indicates image is located on either the left side or the right side of the center.

Standard	Interaural Phase Difference, $\theta$ (Left Ear Leading)								
	105	65	45	25	20	15	10	5	
None	Mean	62.5-L	26.8-L	12.5-L	22.2-L	11.4-L	7.5-L	14.4-L	6.8-L
	S.D.	15.2	10.7	5.4	10.4	5.0	6.1	7.0	4.8
Left	Mean	12.4-R	7.9-R	5.3-R	4.2-R	15.7-R	17.1-R	6.9-R	13.5-R
	S.D.	8.7	9.5	5.7	5.5	10.4	11.9	6.3	6.8
Right	Mean	77.0-L	66.4-L	63.0-L	48.2-L	44.3-L	34.8-L	19.2-L	19.3-L
	S.D.	6.2	9.3	8.5	10.3	11.3	8.9	7.4	6.4

Standard	Interaural Phase Difference, $\theta$ (Right Ear Leading)								
	5	10	15	20	25	45	65	105	
None	Mean	4.8-R	5.9-R	6.5-R	11.3-R	10.6-R	28.0-R	30.4-R	48.7-R
	S.D.	6.8	4.6	4.8	5.0	5.4	10.9	8.3	13.7
Left	Mean	22.8-R	17.1-R	33.7-R	31.8-R	28.7-R	44.4-R	44.6-R	86.3-R
	S.D.	8.4	8.8	10.3	10.6	9.8	10.4	11.0	4.4
Right	Mean	11.7-L	3.6-L	25.4-L	28.6-L	27.4-L	5.6-L	6.1-R	9.4-R
	S.D.	6.9	5.1	7.1	9.1	6.7	4.0	2.7	10.1

Figure 30. Mean lateral image position ( $\bar{P}$ ), in degrees, as a function of interaural phase difference ( $\theta$ ), in degrees, with either the left ear leading in phase or the right ear leading in phase. The size of the standard deviation, in degrees, for each position distribution, is indicated by a vertical bar. Data points are averages over two subjects and for the condition without standard.

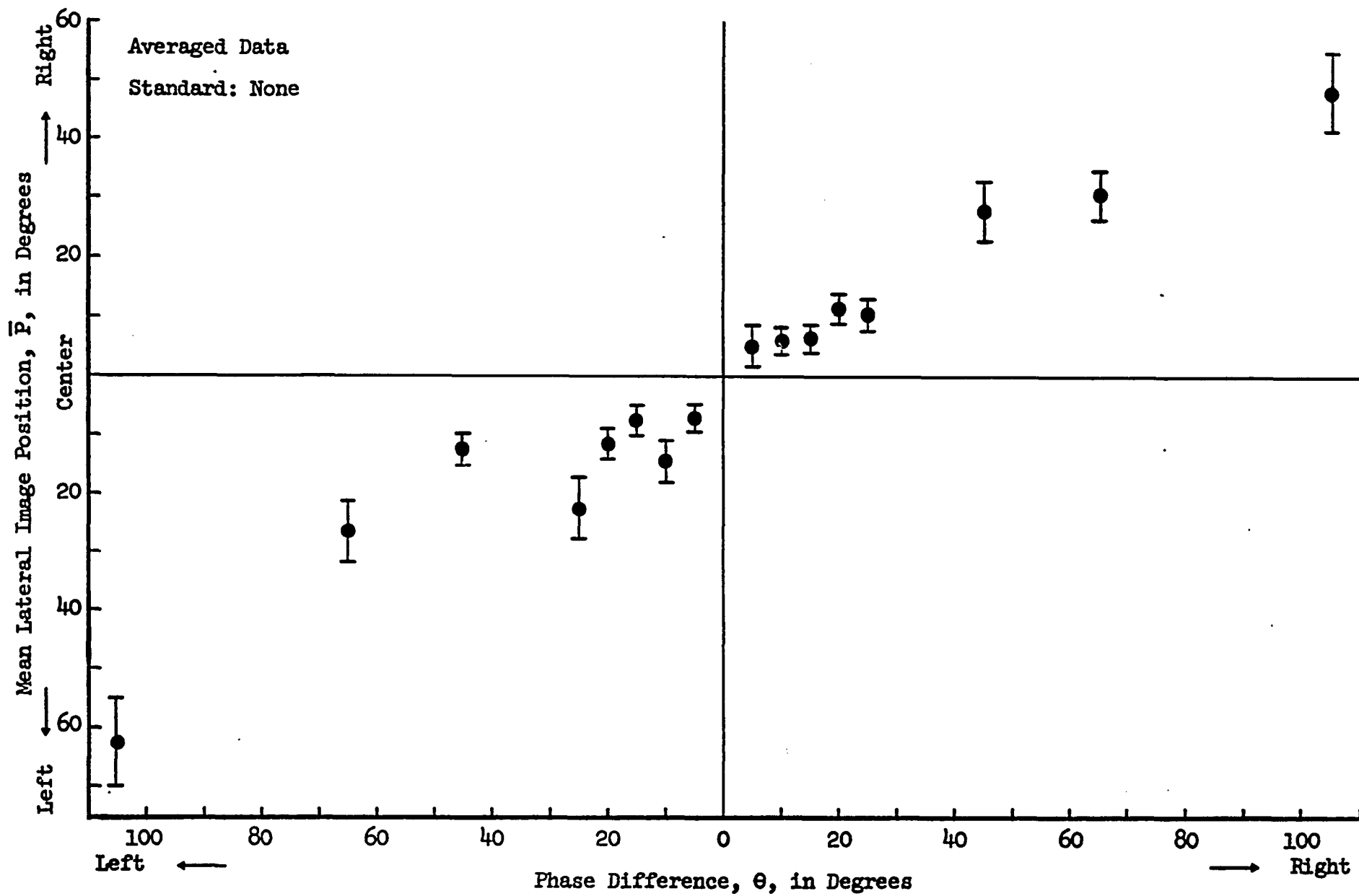


Figure 31. Mean lateral image position ( $\bar{P}$ ), in degrees, as a function of interaural phase difference ( $\theta$ ), in degrees, with either the left ear leading in phase or the right ear leading in phase. The size of the standard deviation, in degrees, for each position distribution, is indicated by a vertical bar. Data points are averages over two subjects and for the condition with the left standard.

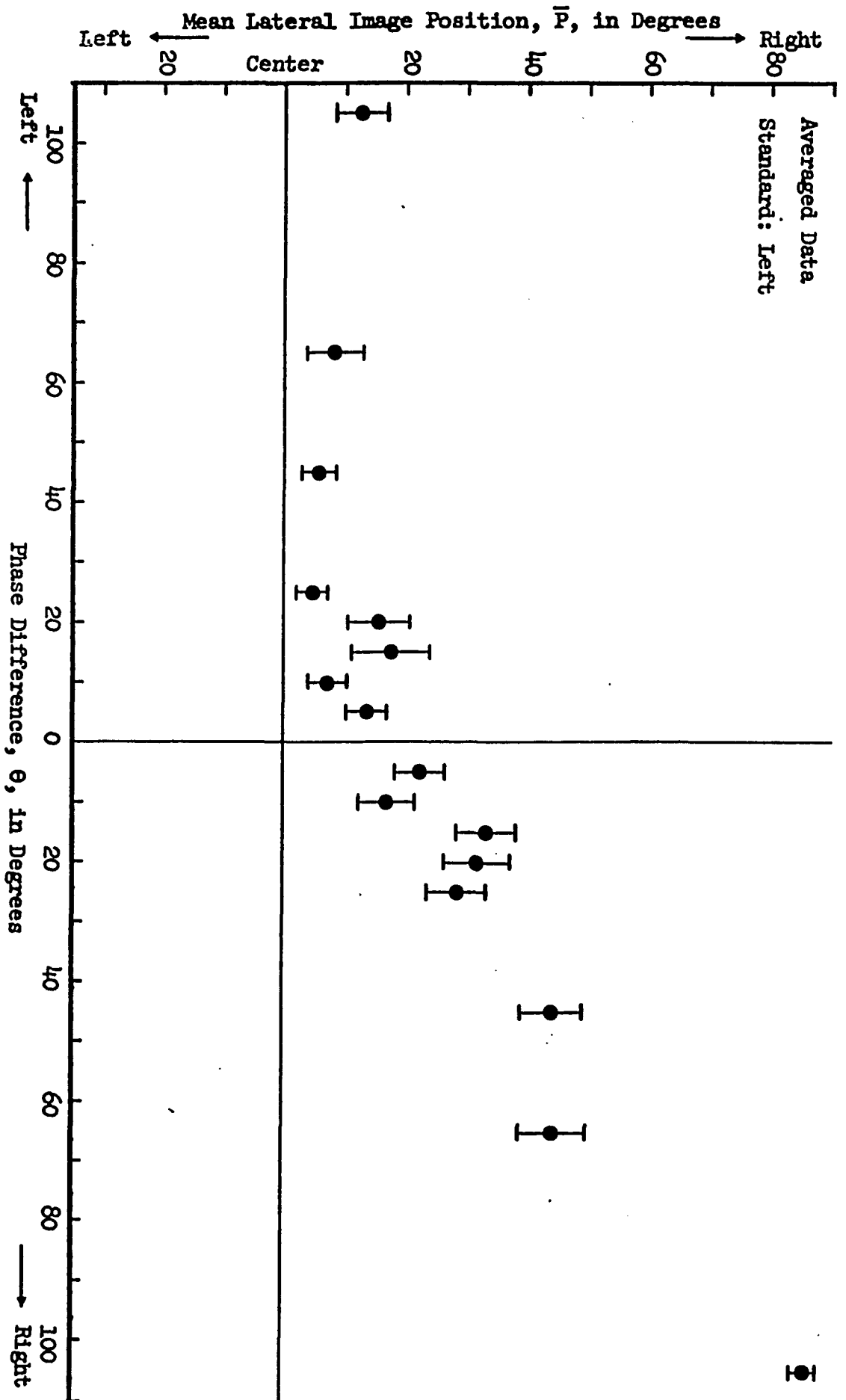


Figure 32. Mean lateral image position ( $\bar{P}$ ), in degrees, as a function of interaural phase difference ( $\theta$ ), in degrees, with either the left ear leading in phase or the right ear leading in phase. The size of the standard deviation, in degrees, for each position distribution, is indicated by a vertical bar. Data points are averages over two subjects and for the condition with the right standard.

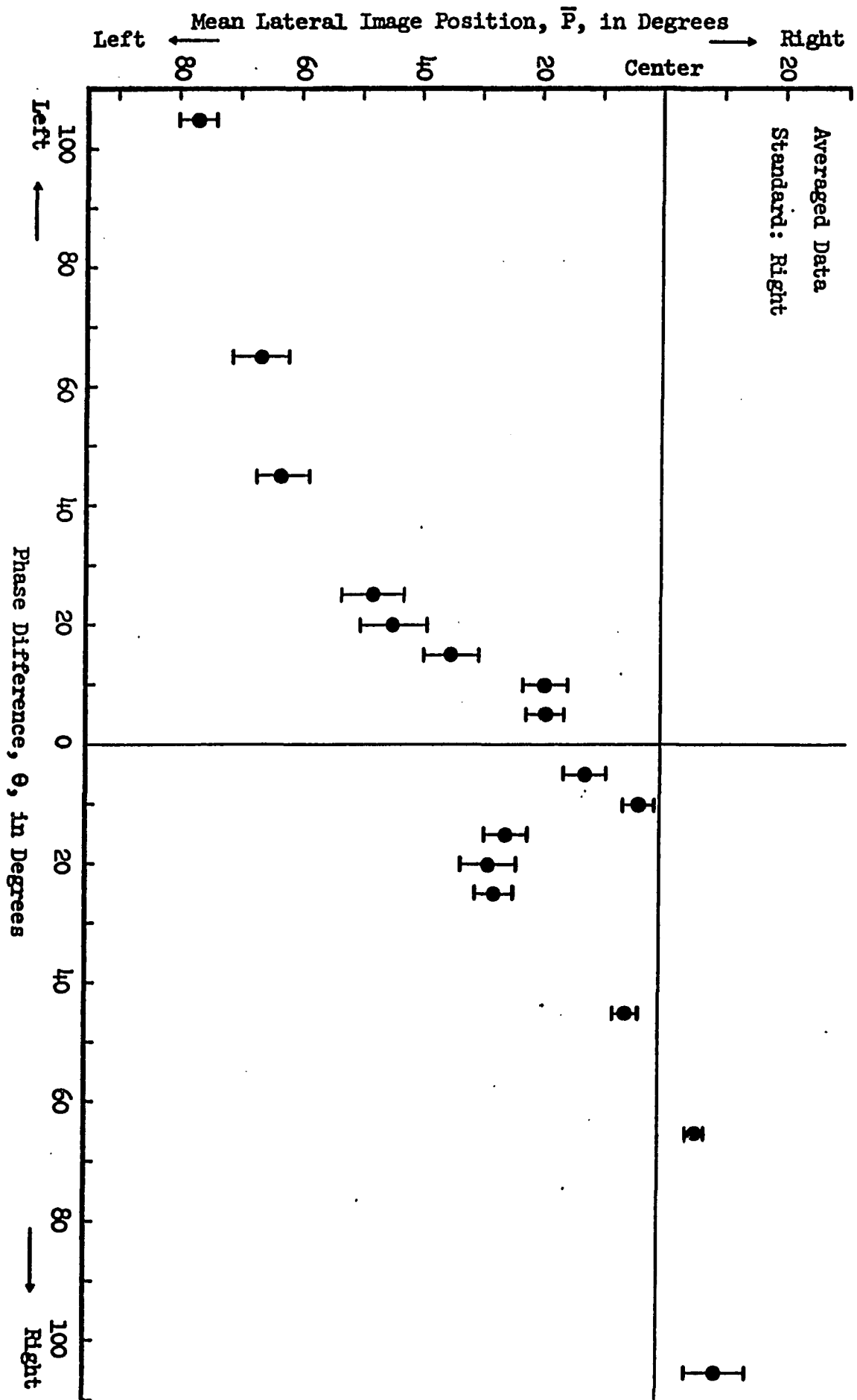
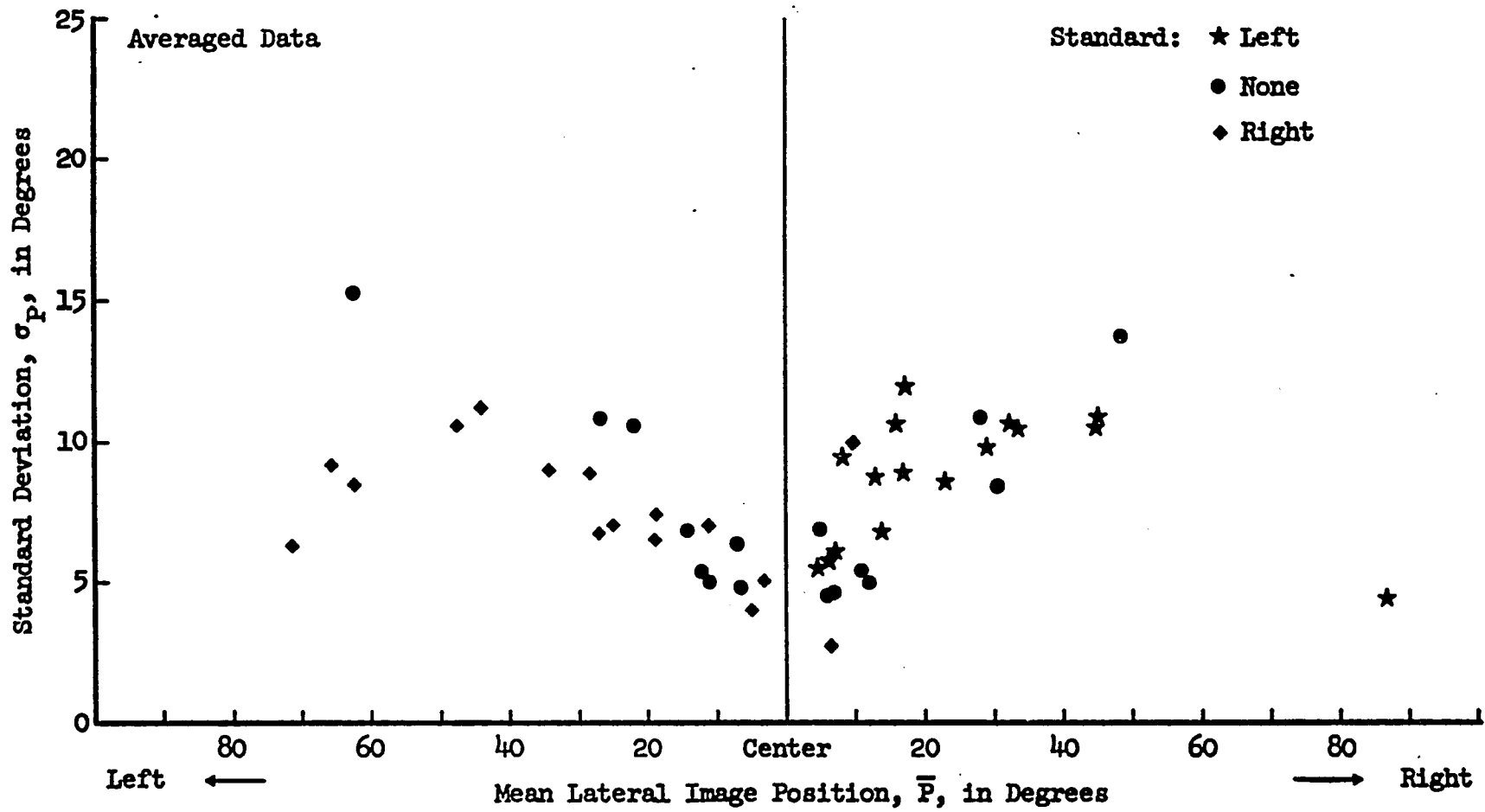


Figure 33. Standard deviation ( $\sigma_p$ ), in degrees, as a function of mean lateral image position ( $\bar{P}$ ), in degrees. Data points are averages over two subjects and include all three conditions of standard.



produced a significant shift in the judgement of binaural lateral image position. (2) A complete quantitative measure of the variance of subjective lateral image position over a wide range has been established which shows a particular functional dependency on the mean of image position itself, and it is not, at least not fully, dependent on physical parameters (e.g., the interaural phase difference) of the stimulus. The function is roughly in the shape of a 'smooth inverted W' (see Figures 25, 26, 27, and 33). The standard deviation ( $\sigma_p$ ) is minimal when the mean lateral image position ( $\bar{P}$ ) locates near the subjective center; it increases to a maximum when the image shifts to about half-way towards either ear from the center; it then decreases to another minimum value when image position reaches the limit near either of the two sides.

Certain additional features of the data of this study will be considered in the course of the text that follows.

#### IV. ADDITIONAL CONTROL CONSIDERATIONS

This study began as preparation for an attempt to compare lateralization judgements with interaural disparity jnd's for the same listeners, where detection and lateralization judgements would be made as nearly contiguous in time as practical. It was decided that the first stage of experimental work would involve only lateral image position judgements with interaural time differences for low frequency pure tones on a high resolution scale, and considerable time was spent to refine the experimental arrangement and computer software for the purpose (see Methods Section), to ensure a most reasonably direct and complete measurement of the properties of subjective lateral image space.

The experimental work was especially difficult because proficiency on the tasks required extensive training. Over a period of about 8 months, work was done with five listeners in an intensive pilot study. Many inversions of subjective position judgements (that is, inversions relative to the ordering of interaural delays in the stimulus) were reflections of the large variability of the pilot data. Three of the five listeners (who did not have any previous experience on psychoacoustics tasks) gave up due to the concentration commitment required, and only the other two listeners (who had served as subjects in psychoacoustic tasks for several years) seemed capable of

producing consistent and reliable data, and finally served as the subjects of this study.

The reason for choosing a 250-Hz tone as the signal was simply that the interaural-time difference is most important for such a low frequency in lateralization. Stimulus duration was found to be a problem during the pilot study. For a signal duration as long as 250 msec, all five listeners reported that the subjective lateral images would move inside the head. In other words, the images experienced by the listeners were neither well-fused nor located in a small region in lateral space. The listeners often felt that an image was located at one spot at the onset of the signal, traversed a short distance (no particular direction could be sensed), and stopped at another locus at signal offset. It was very difficult for the listeners to produce consistent and confident judgements of image position over trials. It was decided that a 50-msec signal would be used, since it allowed listeners to judge the image positions with significantly greater ease and confidence.

In the beginning of the pilot study, a center standard (i.e., standard stimulus presented binaurally without any interaural differences) was used, but listeners consistently reported that the image of that standard was not always perceived at the same spot. Instead, there was sufficient position variability to confuse the listeners and affect their test stimulus judgements significantly. (Note that, in this

study, the binaural stimuli were presented only once in each trial, instead of as a pulsed train as in some previous studies (e.g., Sayers, 1964; Domnitz and Colburn, 1977). It was considered that using pulsed-train stimuli might facilitate the listeners' judgements. However, this might be a consequence of some sort of subjective averaging of the positions of successive images.) It was soon clear that judgements of the image positions for a given stimulus with a certain interaural phase difference would not only vary from trial to trial, but that the center standard enhanced that variability, apparently because its own image was unstable. Thus, finally, it was decided that the pulsed tonal signal (with short duration) would be presented just once in each trial without any reference (standard) as one of the experimental paradigms.

In order to overcome the possible deficiencies of not using any standard as a reference or anchor for subjective lateral position space, each of two monaural standards was tried in the pilot study. With a standard stimulus presented monaurally, its image is well-fused and definitely and consistently located at the appropriate ear. However, it was surprising to find that the introduction of a monaural standard appeared to produce a dramatic shift in the entire set of image position judgements (considering the 500-msec interval). As indicated before (see Introduction Section), the final decision was to conduct the experiment without a standard, with a left

ear monaural standard, and with a right ear monaural standard. By using monaural standards, because of their stable images, it was expected that there would be a reduction of experimental error related to the listener's ability to identify positions in subjective space with the trajectory defined by the mechanical pointer. Furthermore, a very important result was promised in the effects of the standard on the properties of the measured interaural space. Both monaural standard conditions, left and right, were studied, in order to avoid any bias that might result from using only one throughout the entire experiment. This was thought necessary considering that the standard effect might be a consequence of higher cognitive processes (e.g., perceptual set, context, etc.).

In the experiment proper, after collecting all the necessary data, three control procedures were carried out to ensure the reliability of the results. First, since concentration was very important for the listener to produce consistent data and it took about 20 to 30 minutes for a listener to complete one block of trials (i.e., 100 trials), listener fatigue or adaptation might produce some effects on performance. In order to determine the consistency of the data and rule out the effects of such processes, five blocks of data were drawn at random for each listener and each standard condition over different  $\theta$  values. For each such block, the means and the standard deviations were then computed for the first one-third of the block (33 trials)

as well as the last one-third of the block (33 trials), separately. Those results are presented in Table 8. All the four t-values (a correlated t-test was employed), for the mean, the standard deviation, and each of the two listeners, comparing the first one-third and the last one-third of the trials for the selected blocks, yield insignificant results (critical  $|t| = 1.761$  for a two-tailed 0.10 type-one error rate,  $df = 14$ ). In other words, it is concluded that, throughout any block, listeners did perform consistently, not only in generating the judgements of image position but also with respect to the variability of those judgements.

Another concern was that, since a vertical straight line (about one-half inch of overlap with the tip of the pointer) was marked at the top of the semi-circular path of the tip of the pointer (it was used as a reference line to allow the listener to return the pointer to the center position after each trial), then the listener might locate the pointer in a narrower region when images were perceived near the center compared with those away from the center. (The individual distributions of  $P$  for  $\theta = \pm 5^\circ$  for both listeners show a sufficient number of crossings over the midline,  $P = 0^\circ$ , implying that the listeners did not use the line as a strict boundary for their position judgements.) It was considered that the fact that the standard deviations ( $\sigma_p$ ) were found to be smaller when images were perceived near the center might be partially due to the

Table 8. Means and standard deviations (S.D.), in counts of the digital-output, of the first one-third (33) and the last one-third (33) of the trials for each of 15 blocks of data (selected at random). Letter L or R following each  $\theta$  value indicates the binaural signal has either the left ear or the right ear leading in phase, accordingly. For a detailed explanation, see text.

		Subject							
		HT				PT			
		Mean		S.D.		Mean		S.D.	
		Trials 1-33	Trials 68-100	Trials 1-33	Trials 68-100	Trials 1-33	Trials 68-100	Trials 1-33	Trials 68-100
$\theta$									
Left Standard	105°-L	3240	3238	83.5	87.0	3016	3047	66.3	46.8
	45°-L	3152	3183	29.7	41.4	3043	3067	41.4	40.1
	25°-L	3146	3136	19.4	31.0	3101	3070	44.5	38.2
	10°-L	3133	3105	25.5	37.6	3112	3093	53.4	52.6
	10°-R	3165	3184	32.8	49.9	3169	3165	59.4	95.8
Without Standard	65°-L	3067	3011	51.2	47.0	2866	2752	51.0	71.6
	5°-L	2966	2992	62.9	45.1	3082	3049	30.1	43.1
	15°-R	3135	3124	24.1	27.0	3110	3104	29.8	41.2
	65°-R	3282	3287	60.5	60.4	3273	3275	71.9	70.8
	105°-R	3448	3400	89.9	121.3	3355	3396	100.5	106.8
Right Standard	45°-L	2547	2530	115.3	94.0	2615	2616	56.8	52.9
	25°-L	2509	2622	81.4	58.7	2672	2712	78.3	81.7
	5°-R	2996	2992	24.9	31.3	2888	2892	50.2	45.1
	25°-R	2983	2982	43.3	37.8	2744	2741	53.1	89.7
	65°-R	3099	3103	27.8	20.4	3096	3112	11.2	10.6
t-value		-0.138		-0.306		0.345		-1.482	

existence of that particular reference line. In order to evaluate the seriousness of such an effect, instead of using one straight line marked on the top, two straight lines were marked, one towards each side at an angle of  $45^{\circ}$  away from the center (each having the same length and overlap with the pointer as the middle line, see Figure 34). There was no middle line in this control study. Four different stimulus conditions were selected and data were collected by using a procedure identical to the regular experimental procedure, except that the listener was instructed to return the pointer to the center by eye. Results for standard deviations of this control study for the two listeners (analyzed by the same method used for the experimental data) and the corresponding results for standard deviations from the main study with the same stimulus conditions (without standard) are both listed in Table 9. Figure 35 represents the average values of the standard deviation,  $\sigma_p$ , from Table 9, plotted as a function of interaural phase difference,  $\theta$ . An analysis of variance for repeated measurements design (Myers, 1966) shows the four differences between the two studies to be insignificant. Visually, the control and experimental patterns for  $\sigma_p$  as a function of  $\theta$  (see Figure 35) are clearly in agreement, and it can be concluded that the middle reference line did not create a significant effect in the determination of the standard deviations of the lateral image position judgements.

Figure 34. Drawing of mechanical pointer device (part of Figure 13). Note that, in the control study, two straight lines (illustrated by dashed lines) were marked and the middle reference line was removed.

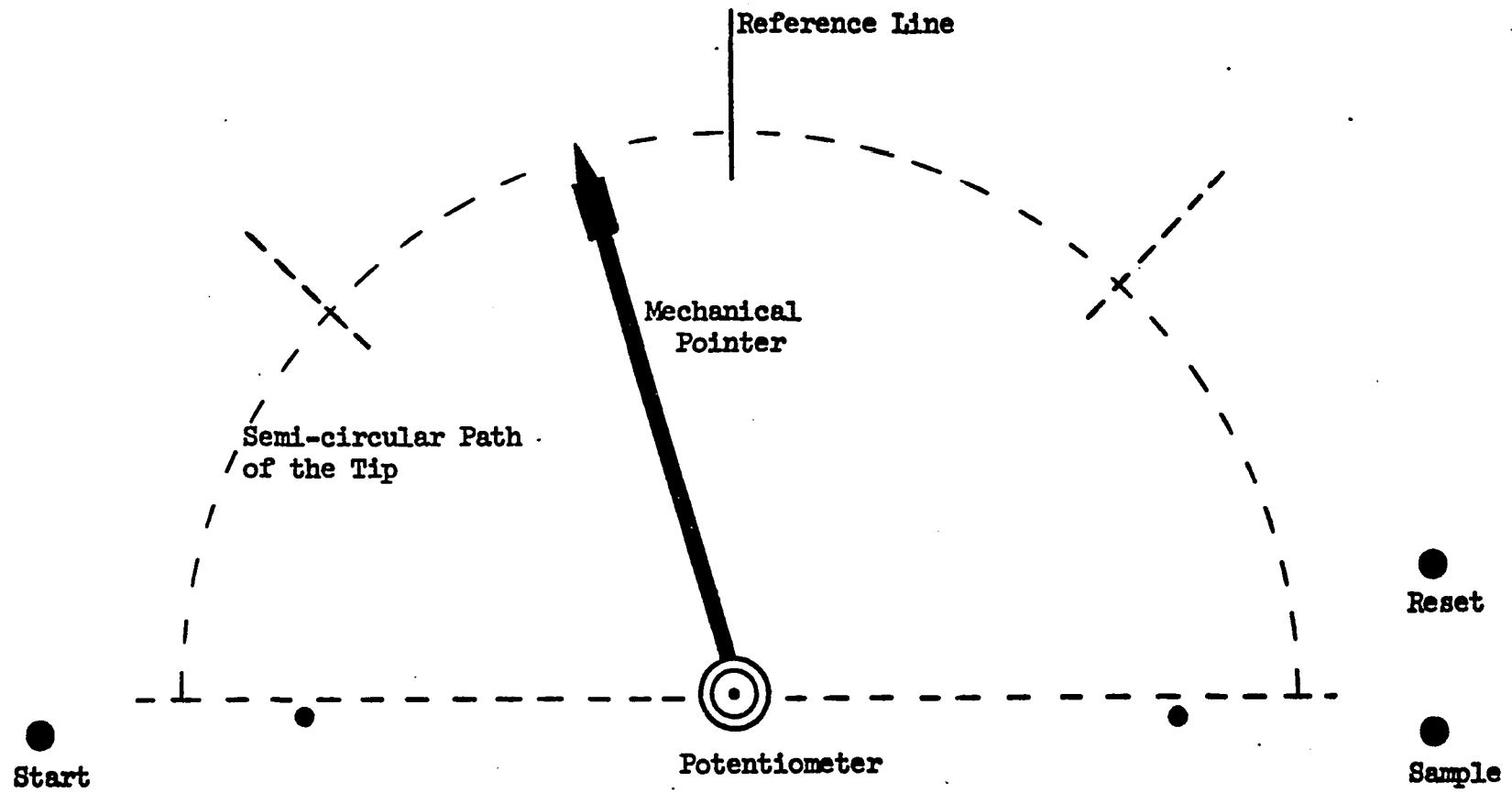
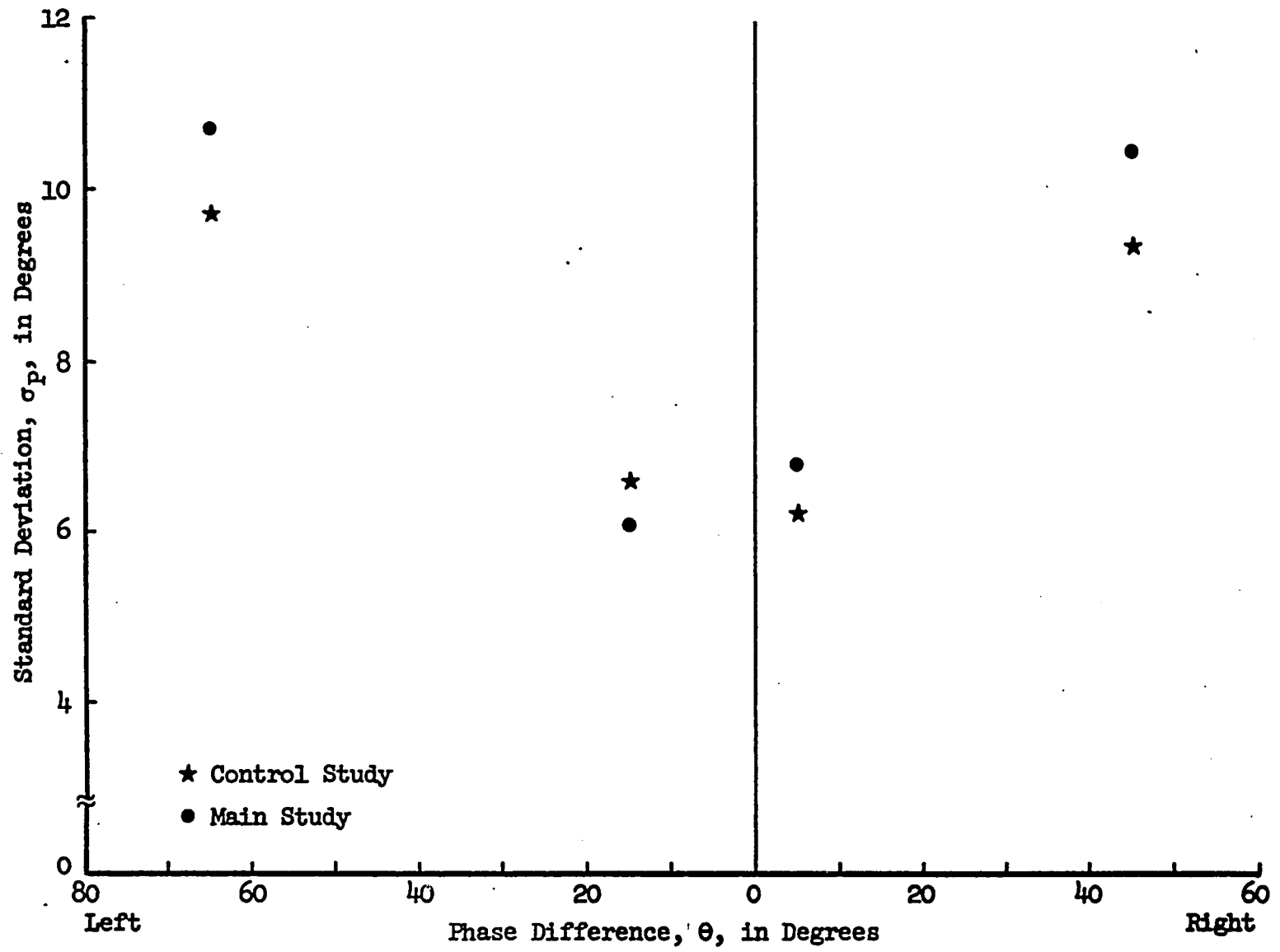


Table 9. Standard deviations, in degrees, of lateral image position distributions for four selected interaural phase differences ( $\theta$ ) without standard. Data listed include those for the control study as well as corresponding results for the main experimental study. Letter L or R following each  $\theta$  value indicates that either the left ear or the right ear leads in phase, accordingly. For a more detailed explanation, see text.

		$\theta$ (in degrees)			
		65-L	15-L	5-R	45-R
Control Study	HT	10.5	6.1	8.3	9.3
	PT	8.8	7.1	4.1	9.5
	Average	9.7	6.6	6.2	9.4
Main Study	HT	10.3	5.2	6.0	7.5
	PT	11.1	6.9	7.6	13.4
	Average	10.7	6.1	6.8	10.5

Figure 35. Standard deviations,  $\sigma_p$ , after averaging across the two listeners as a function of interaural phase differences,  $\theta$ . The graph shows the results of the reference line control study and comparable results of the main study.



A further (modest) issue concerns the process of mapping identified subjective image position in the head to the analogue scale by asking listeners to communicate their judgements with the mechanical pointer (even if the method is a considerable improvement compared with previous studies, see Methods Section). More specifically, for a given stimulus condition, the standard deviation,  $\sigma_p$ , and variations of  $\sigma_p$  with  $\bar{P}$ , might be partially due to such a psychophysical procedure (i.e., using a motor-response on a visual scale to represent the judgement of lateral image position). For example, it is not absurd to consider that the variations of  $\sigma_p$  with  $\bar{P}$  might be a consequence of the structure of the head, particularly the locations of the nose, eyes, and ears, and their role in defining an interaural space. Thus, in an attempt to check the validity of the method used in this sense, the tactual modality was selected, in order to substitute for the binaural sensation. An adjustable elastic band was made and put around the subject's head. A tack was then placed at a fixed position on the elastic band with the tip of the tack towards the surface (skin) of the forehead. Without wearing the earphones, the subject was required to press the tack to produce a pressure sensation on the forehead, and then to move the pointer to a location which the subject felt could properly represent the locus of that pressure sensation. (This defined one trial.) Two different positions on the elastic band were selected for each subject.

Position judgement data were subsequently collected and analyzed by a procedure similar to that used in the main experiment, except that it was not possible to present multiple stimuli at closely neighboring locations, or in random order, or without the subject knowing in advance which stimulus was selected. However, tack positions on the elastic band were determined without conscious consideration by the subjects as to their angular values. For subject HT, the two positions were 2 cm to the left side and 6 cm to the right side of the center; for subject PT they were 8 cm to the left side and 3 cm to the right side of the center. (Center refers to the medial sagittal plane of the head with the band in place.) By using a linear transformation considered only after the data were collected, those four figures could be replaced by  $11^{\circ}$  to the left side and  $32^{\circ}$  to the right side for HT and  $48^{\circ}$  to the left side and  $18^{\circ}$  to the right side for PT, respectively. The resulting subjective position distribution means and standard deviations for all four tack positions are presented in Table 10. According to Table 10:

(a) The resulting mean position judgements using the sensation to mechanical pointer translation nearer the midline are excellent representations of the actual loci of the tactual sensations (considering that the subjects did not know the angular deviation values). (b) The total variance (or standard deviation) values, which are due to the translation and tactual sensation position, are considerably smaller than the corresponding

Table 10. Means and standard deviations (S.D.), in degrees, of pressure sensation locus distributions for variations in tack position on the elastic band. Letter L or R following each mean value indicates sensation locus is located on either the left side or the right side of the center, accordingly. For a detailed explanation, see text.

Subject	Tack Position	Mean	S.D.
HT	2 cm ( $11^{\circ}$ ) Left Side	11.5-L	1.8
	6 cm ( $32^{\circ}$ ) Right Side	35.7-R	1.9
PT	8 cm ( $48^{\circ}$ ) Left Side	59.4-L	2.7
	3 cm ( $18^{\circ}$ ) Right Side	18.2-R	2.7

values resulting from the binaural study (see Tables 4, 5, and 6), and are comparable to the values from the mechanical setting alone. Therefore, the tactual sensation itself produced negligible variance, and the mapping from sensation at the head to pointer position can be ignored as a source of variance in the main study. This assumes the qualification that the subjects diligently tried to map their sensations with the pointer trial by trial, and did not try to reproduce pointer locations. (c) Although the tactual standard deviation values are small, they are consistent for each subject independent of position, so, given the qualifications just mentioned, it seems that the structure of the head has no influence on the relation between  $\sigma_p$  and  $\bar{P}$  for the tactual stimuli. This does not resolve the issue for the auditory stimuli, and the randomization of closely spaced tactual  $\theta_i$  would have been a better control, but had the tactual results been otherwise and showed a dependence of  $\sigma_p$  on  $\bar{P}$ , the interpretation of the binaural data would certainly have had to be considered contaminated. Thus, it is tentatively concluded that the psychophysical procedure using the mechanical pointer is reasonably valid and has not contaminated the results of the main experiment.

Each listener in this study was always extremely diligent in doing his/her best to have the earphones positioned consistently throughout the data collection procedure. Nevertheless, it is

necessary to consider that variation of positioning of the headphones in any binaural task may produce alterations of interaural amplitude and interaural phase differences (Hershkowitz and Durlach, 1969). The use of small insert microphones attached to the headphones as a monitoring device (Domnitz, 1975) was not possible for this study for practical/technical reasons. Nevertheless, the following control arguments provide adequate justification for the assumption that both the interaural amplitude and interaural phase differences for the acoustical signals at the ears were not significantly different from the values set electronically. For the no standard condition: (a) There are no left-right inversions such that  $\bar{P}(\theta < 0^\circ) > 0^\circ$  or  $\bar{P}(\theta > 0^\circ) < 0^\circ$  for either listener. (b) The  $\bar{P}(\theta)$  and  $\sigma_p(\theta)$  results are symmetrical about  $\theta = 0^\circ$ , and so are the results for distribution skewness (see Figure 37 of the Discussion Section). (c)  $\bar{P}(\theta = \pm 5^\circ) \approx \pm 5^\circ$ , and sensitivity to a shift in interaural phase difference (Yost, 1974) is known to be greatest nearest the midline. (d)  $\sigma_p(\theta)$  is small for small  $|\theta|$  as compared to large  $|\theta|$ . Note that even if significant earphone imbalances existed, the interpretation of the results of this study would be unaltered given the effect of the standard and the resulting conclusion that  $\bar{P}$  is the relevant variable to consider for interaural space, and not  $\theta$ . (Other features of the results, to be discussed at length subsequently, also render the problem of headphone positioning

insignificant.)

One last point to be made in the nature of control considerations concerns the basis of the data analysis procedures. That is, combining of the local distributions of  $P(\theta_i)$  for the four  $\theta_i$  for each  $\theta$  presumed that the  $\theta_i$  were sufficiently close, so that the local theoretical distributions from which the  $P(\theta_i)$  were sampled can be superimposed simply by a lateral shift (equivalent to adjusting  $\bar{P}_i$  so that  $\bar{P}_i = \bar{P}$  for all  $i$ ). Examination of the standard deviations for the local distributions for different experimental conditions for each listener reveals that  $\sigma_P(\theta_i) \approx \sigma_P(\theta)$  for all  $i$ . That is, the four local distributions corresponding to a given  $\theta$  value have almost the same variance. This further justifies the procedure for shifting and combining each set of four  $P(\theta_i)$  distributions to obtain one corresponding  $P(\theta)$  distributions.

## V. DISCUSSION

Having tentatively dismissed any doubts that the results of this study represent a reasonably direct measure of the statistical properties of subjective lateralization judgements, the first theoretical issue can be addressed. The idea that listener performance in various binaural experiments, both objective (e.g., discrimination, detection, masking) and subjective (e.g., position matching, pointing) is based on judgements of subjectively experienced lateral image position is widely accepted and has been implicit in binaural theory. The position-variable model (proposed by Stern and Colburn, 1978) is the most recent and complicated, and provides an elaborate quantitative base for generating the statistical position variable  $P$  ( $P$  is equivalent to  $\hat{P}$  of Stern and Colburn, see Introduction). However, the simple working assumption of the existence of  $P$  as a unidimensional position variable specified statistically as Gaussian,  $N(\bar{P}, \sigma_P)$ , was made by Domnitz and Colburn (1977). Its statistical properties can be said to have never been measured directly with the exception of this study and possibly the studies of Sayers (1964) and Yost (1973). Other studies (e.g., Moushegian and Jeffress, 1959; Domnitz and Colburn, 1977) which used acoustical pointers to relate  $\theta$  to lateral position judgements cannot be considered in the same sense as this one, because they implicitly or

explicitly, as discussed by Stern and Colburn (1978), assume at least monotonic transforms to relate binaural phase differences ( $\theta$ ) to position judgements ( $\bar{P}$ ) and then  $\bar{P}$  to the acoustical pointer scale (e.g.,  $\Delta I$ , or  $\theta$  for noise).

Sayers (1964) used a scale of 21 numbers placed on a card mounted in front of the listener, from which a value was apparently selected on each trial to indicate the image position of the binaural stimulus. The spatial relationship of the physical scale relative to the listener's head was not described, and, unfortunately, the details of the experimental procedure, particularly the temporal parameters of signal presentation, were not clearly described either. With regard to the statistics of  $P$ , Sayers presented one scatter diagram of individual position judgements for one listener for a 600-Hz pure tone in his Figure 2. This is the earliest and one of the only two published data sets containing such information regarding position variability, and is further limited in the sense that the position scale used was so vaguely specified. All other results presented in his paper are averages. Although Sayers offered no calibration relating his dependent number scale to physical interaural position measured in degrees, the results show his average subjective position values to be monotonically, and, in fact, approximately linearly related to  $\theta$  over the range where  $|\theta| \leq 120^\circ$ . Near the limits of and beyond that range Sayers reported evidence for multiple images and position

reversals.

Yost (1973) used a procedure similar to Sayers', except that Yost also introduced a reference stimulus. In his study, the observer (only one) was presented a 13 unit train of 100-msec, 200-Hz tone bursts. The first five stimuli in the train had no interaural phase differences and served as a reference condition (i.e., center standard), while the next eight stimuli had an interaural phase difference and served as a test stimulus. The observer marked on a data sheet (premarked with a diagram of the head) which of 21 positions the last 8 stimuli occupied in his head. The results from that study showed that  $\bar{P}$  (averaged over only 8 trials) also appeared approximately linearly related to  $\theta$  over the range where  $|\theta| \leq 120^\circ$ , in agreement with Sayers. Considerable variability, represented by the range, was obtained in the lateral position judgements, especially as the image position moved away from the center. Those limited range measurements by Yost are related to  $\sigma_p$  and provide some results (however vague) in agreement with this study. Nevertheless, both sets of data (Sayers and Yost) contain information related to  $\sigma_p$ , even though they provide only very limited specification of the statistics of P.

Note that, the data from Yost's study suggest that the image moves from the center towards one ear as the interaural phase difference increases from 0 to 180 degrees. Sayers argued that the image moved from the center towards one ear as the interaural

phase difference increased from 0 to 90 degrees and then back to the midline as the interaural phase difference increased further from 90 to 180 degrees. The data in Sayers' (1964) Figure 2 show that past an interaural phase difference of approximately  $120^\circ$  his listeners sometimes indicated that images were on the opposite side of the head. For an interaural phase difference of  $180^\circ$  many listeners said that the image was at midline. Yost argued, on the other hand, that both of those 'judgement errors' could be eliminated if (1) great care was used in positioning the observer's headphones, and (2) the observer was provided a reference condition for each judgement. It might be true that Sayers did not use these precautions, and his data are far more variable than those obtained by Yost. The pilot experiences of listeners in this study indicated agreement with the Sayers limitations of the span of  $\bar{P}$ , with or without standard, which led to the decision to allow  $\theta$  to range only between  $\pm 105^\circ$ . Both listeners consistently perceived well-fused images with variations of  $|\theta| \leq 105^\circ$ .

More specifically, regarding the statistical properties of  $P$ , Sayers' (1964) Figure 2 suggests that  $\sigma_P$  increases for large values of  $|\theta|$ , approaching the cue-reversal points of about  $\pm 120^\circ$ , where very large variance is reflected in the report of two values of  $\bar{P}$ , one near each end of the position scale. Yost's (1973) results for the range also suggest that  $\sigma_P$  increases for large values of  $\theta$ , and has very large values

when  $\theta$  increases up to about  $\pm 150^\circ$ .

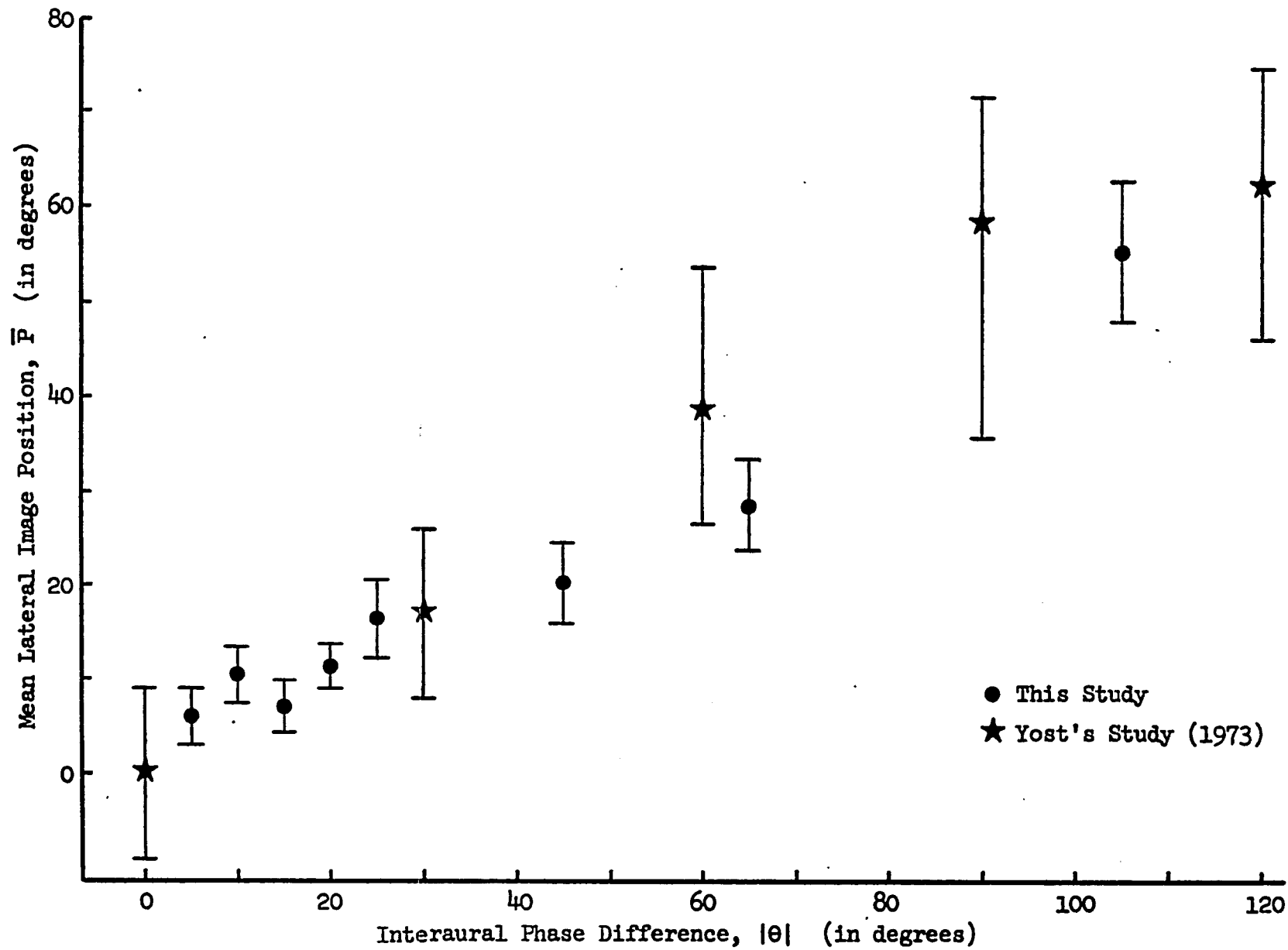
In the study reported here the overall trend (ignoring local irregularities) relating  $\bar{P}$  to  $\theta$  (without standard) is roughly linear such that  $\bar{P} \approx \theta/2$  (for  $|\theta| \leq 105^\circ$ ). Table 11 presents results for  $\bar{P}$  and  $\sigma_p$  averaged over the directions left and right for the average results over the two listeners (see Table 7), since there were no inversions where  $\bar{P}(\theta < 0^\circ) > 0^\circ$  or  $\bar{P}(\theta > 0^\circ) < 0^\circ$ . Figure 36 represents those averaged  $\bar{P}$  values (over the two direction of  $\theta$ ) plotted as a function of  $|\theta|$  (i.e.,  $\bar{P}(|\theta|)$ ), and averaged  $\sigma_p$  values are represented by vertical bars. Note that the data points for  $\pm \theta$  are replicas of each other, based on the assumption (which is supported by the data) that the underlying  $\bar{P}$  and  $\sigma_p$  values are left-right symmetrical with respect to  $\theta = 0^\circ$  (given no standard).

In order to have a closer comparison, Yost's (1973) data are also reconstructed by two steps: (1) data of means were averaged over the directions left and right (as above) and the 21-point visual scale was then approximately translated into degrees by a linear transformation (the whole range over 21 points was assumed to be  $180^\circ$ ); (2) values of range were read out and the larger one for the same  $|\theta|$  over the two directions (left and right) was then used to represent the range (over two directions) over  $|\bar{P}|$ . In Figure 36, those values of  $\bar{P}$  are plotted as a function of  $\theta$  and the corresponding range values are represented by vertical bars.

Table 11. Means ( $\bar{P}$ ) and standard deviations ( $\sigma_p$ ), in degrees, averaged over directions left and right and over the two listeners, of lateral image position distributions for variations in (absolute) interaural phase difference ( $|\theta|$ ), in degrees. Data listed are those for the condition without standard.

	Interaural Phase Difference, $ \theta $ (in degrees)							
	5	10	15	20	25	45	65	105
$\bar{P}$	5.8	10.2	7.0	11.3	16.4	20.2	28.6	55.6
$\sigma_p$	5.9	5.9	5.5	5.0	8.3	8.6	9.6	14.5

Figure 36. Mean position ( $\bar{P}$ ) (averaged over the directions left and right), in degrees, as a function of absolute value of interaural phase difference ( $|\theta|$ ), in degrees, for the condition without standard. The size of the standard deviation (averaged over two directions), in degrees, is indicated by a vertical bar. Data are also plotted from Yost (1973). For a detailed explanation, see text.



After examining Figure 36, it is clear that the results of this study are in good agreement with Yost's. Both studies show that  $\bar{P}$  is approximately a linear function of  $|\theta|$ . By employing a 'least-squares' method, linear regression lines constrained to pass through  $(\bar{P}, \theta) = (0, 0)$  for the two sets of data were determined to be  $\bar{P} = (.508)\theta$  for this study and  $\bar{P} = (.578)\theta$  for Yost's study. (Note that computation of the linear regression line for this study is based on the assumption that  $\bar{P}(\theta = 0^\circ) = 0^\circ$ .) Obviously, the two regression lines are very similar to each other.

With regard to  $\sigma_p$ , Yost's range measurements show a trend similar to that of this study such that the variability appears to increase as  $\theta$  increases. Given a normal distribution from which to sample, a rough approximation is that the range is about 6 times the standard deviation. Based on the working assumption that the distribution is approximately  $N(\bar{P}, \sigma_p)$  (Domnitz and Colburn, 1977), Yost's data for ranges could then be replaced by  $\sigma_p \approx (1/6)(\text{Range})$ . After doing so, it seems that the measurements of variability by Yost have relatively smaller values as compared to this study. To account for this discrepancy, several arguments related to methodology can be raised as follows: (1) Yost used a train of eight tone bursts (each 100 msec) as the test stimulus (instead of one 50-msec tone burst as in this study). On each trial, the listener determined his subjective P based on a sequence of 8 perceived

images. Less variability should be obtained because the listener should have ignored extremes of the 8 samples by reporting  $P$  in accordance with their central tendency. In other words, in Yost's study, for any given  $\theta$ ,  $\bar{P}$  might be determined by (the listener) dropping some extreme values as compared to this study.

(2) A 21-category visual scale was used in Yost's study and it forced the listener to select one of those 21 categories, as the one closest to  $P$ , to represent his judgement. Since the 21-point scale represents the entire span of  $P$  (i.e.,  $180^\circ$ ), the intervals are  $9^\circ$  wide. On each trial, this particular visual scale would force the listener to round his judgement by  $\pm 4.5^\circ$ . It might thus reduce the values of the variability (i.e., range) measurements. Compared to Yost's study, the continuous linear scale used in this study would provide more precise measurements. Note that  $\pm 4.5^\circ$  is relatively large compared to the  $\sigma_P$  data reported in this study. (3) In Yost's study,  $\theta$  was presented at random on each trial with a spacing of  $30^\circ$ , a value way above the size of the jnd for interaural phase discrimination, which, at minimum, is about 2 degrees. On the other hand,  $\theta$  was randomized by using a  $2^\circ$  spacing in this study. For the wider spacing, the listener may more readily select one of the several regions of the subjective position scale associated with the various stimuli, and then set his response to reflect the middle of that region. That might be another reason why the measurements of variability for Yost's listener appear relatively smaller. In

this study, the narrow spacing was used to force the listener to be precise within the local region.

For either interaural time differences or interaural intensity differences most previous data on lateral image position judgements are fairly symmetrical about the mid-line ( $0^\circ$  or 0 dB) (e.g., Sayers, 1964; Yost, 1973; Domnitz and Colburn, 1977). In this study the results for  $\bar{P}(\theta)$  for the condition without standard are in agreement with those studies. In addition, the results for  $\bar{P}(\theta)$  clearly support the assumption that  $\bar{P}(\theta = 0^\circ) = 0^\circ$ . Consequently, the regional slope of the function  $P(|\theta|)$  in Figure 36 appears high near  $|\theta| = 0^\circ$ , such that  $\bar{P}(|\theta|) \approx |\theta|$ . (The slope decreases as  $\theta$  grows beyond about  $\pm 10^\circ$ .) It has been discussed before that, for any given  $\theta$  and standard condition, although four actual  $\theta_i$  were selected ( $2^\circ$  spacing) and randomized across trials within a block, both listeners in this study were consistently able to locate four closely spaced binaural images in an appropriate lateral order corresponding to the different interaural phase shifts. (see Table 3 and Results Section). In other words, for any given block, listeners were not only able to determine the image position for a particular nominal  $\theta$ , but were also able to discriminate the four actual  $\theta_i$  by carefully selecting different locations of the image positions. For the record, slopes of the regression lines for the sets of four actual  $\theta_i$  values (see Figure 16 for an example; note that the unit was changed

into degrees) over the total range of  $\theta$  appear in Table 12.

Unfortunately, no particular pattern can be readily discerned in Table 12. However, the slopes of the local functions of  $\bar{P}(|\theta_1|)$  (over four actual  $\theta_1$ ) for the condition without standard only, were averaged for each  $|\theta|$  over two listeners and over the directions left and right. Table 13 represents those averaged data of local slopes for the sets of four actual  $\theta_1$  without standard. The overall slope of the function  $\bar{P}(|\theta|)$  was determined to be .508 (or .481 when computed without the constraint including (0, 0), which could not logically be used for the local slopes). It is clear that the averaged local slopes are significantly higher than the overall slope (at worst,  $t = 5.615$ ; critical  $|t| = 5.405$  for a two-tailed 0.001 type-one error rate,  $df = 7$ ).

The above finding is puzzling. It appears to be related to a result obtained in studies of monaural intensity resolution by Pynn, Braida, and Durlach (1972). They found that the resolution obtained in a one interval intensity identification experiment with a fixed number (10) of stimuli, as represented by their cumulative sensitivity function  $d'(I_1; I_N)$ , is greater for a smaller range task. In other words, the slope of the function relating sensitivity ( $d'$ ) to range ( $I_1/I_N$  in dB) decreased with an increase in stimulus range. This was qualitatively consistent with their theory (Durlach and Braida, 1969; Braida and Durlach, 1972) and supposedly reflects the growth of (memory) variance

Table 12. Slopes of the regression lines for the sets of four actual  $\theta_1$  values for variations in interaural phase difference,  $\theta$ , in degrees. Data listed include those for two listeners and three standard conditions. Data underlined indicate negative slopes.

Stan- dard	Sub- ject	Interaural Phase Difference, $\theta$ (Left Ear Leading)							
		105	65	45	25	20	15	10	5
None	HT	1.489	0.772	0.527	1.543	0.790	0.815	0.969	0.883
	PT	0.204	0.978	0.827	0.925	0.380	0.800	0.574	0.913
Left	HT	0.118	0.625	0.110	0.353	0.691	0.809	0.542	0.514
	PT	<u>0.013</u>	<u>0.007</u>	0.707	0.620	0.124	0.581	0.292	0.743
Right	HT	0.600	0.581	0.890	1.021	1.096	2.130	0.407	0.753
	PT	0.097	0.367	0.048	0.189	0.147	0.060	0.569	0.706

Stan- dard	Sub- ject	Interaural Phase Difference, $\theta$ (Right Ear Leading)							
		5	10	15	20	25	45	65	105
None	HT	0.868	0.375	0.958	0.640	1.206	1.537	0.717	0.474
	PT	1.385	1.479	0.611	0.222	0.146	0.388	1.709	0.203
Left	HT	0.860	0.669	1.993	1.539	1.388	1.086	0.894	0.064
	PT	0.967	1.625	1.250	0.941	0.322	0.817	0.039	<u>0.079</u>
Right	HT	0.660	0.453	0.778	1.163	0.944	0.319	0.097	0.051
	PT	0.327	0.467	<u>0.054</u>	0.222	0.189	<u>0.006</u>	0.058	0.361

Table 13. Averaged local slopes over two listeners and two directions left and right for variations in (absolute) interaural phase difference, in degrees. Data listed include those only for the condition without standard.

	Interaural Phase Difference, $ \theta $ (in degrees)							
	5	10	15	20	25	45	65	105
Slope	0.987	0.849	0.796	0.580	0.955	0.820	0.887	0.593

with an increase in range. The present study is a small range (position) identification experiment. The high local  $\bar{P}(\theta_i)$  slopes as compared to the overall slope of  $\bar{P}(\theta)$ , which is about the same as for Yost's (1973) large range (spacing of  $30^\circ$ ) study, also suggests that resolution is better for the smaller range. Furthermore, for each  $\theta$ , the local  $\bar{P}(\theta_i)$  distributions had nearly the same variance;  $\sigma_P(\theta_i) \approx \sigma_P(\theta)$  for all  $i$ . Thus, the small range lateralization task appears to yield a spread of the mapping of  $\theta$  to  $P$  in a local region, so that the  $\bar{P}_i$  for neighboring  $\theta_i$  are farther apart than would be expected from the overall  $\bar{P}(\theta)$  and  $\sigma_P(\theta)$  results. (This may also contribute to explaining the differences between Yost's range data and the values for  $\sigma_P$ .) The predictions for jnd's at different values of  $\theta$  would therefore be smaller using the local slopes, and this is compatible with the main finding of Pynn, Braida, and Durlach (1972), that intensity resolution in a two interval discrimination experiment is approximately the same as resolution in a small range identification experiment.

Having  $\bar{P}$  and  $\sigma_P$  as functions of  $\theta$ , predictions can justifiably be made for discrimination experiments presumed to depend on subjective position, if the approximation to normality is acceptable (normality characteristics of the subjective position distributions will be discussed later), as supposed by Domnitz and Colburn (1977). The general Central Limit Theorem (Hays and Winkler, 1971) and notions of the variability of neural

firing and a neural code for position make such an assumption reasonable. If the neural code is corrupted by Poisson neural noise and that is transformed to the P scale by coincidence counting as idealized by Stern and Colburn (1978), the Gaussian assumption is also a consequence of the normal approximation to the Poisson when the mean number of coincidence counts associated with  $\bar{P}$  is fairly large. (Note here that Jeffress (1965) has also assumed Gaussian corruption of interaural delays in an attempt to explain Huggin's (Cramer and Huggins, 1958) binaural pitch and binaural unmasking.)

Nevertheless, there is some reason to suspect that the distributions of P may not be normal as  $\bar{P}$  moves towards either ear and away from the center, due to the lateral bounds exhibited by both cue reversal phenomena (Sayers, 1964; Sayers and Cherry, 1957) and also the effects of the monaural standards (see Figures 28, 29, and 33) reported here. That is, it is suggested that the distribution of P may be more and more skewed towards the contralateral side (ear) as  $\bar{P}$  moves away from the center. Consequently, the distributional shapes of  $P(\theta)$  were evaluated by using the Chi-square goodness of fit test for normality, and also by computing estimates of skewness using the formula:  $G = m_3 / m_2(\sqrt{m_2})$ , where  $m_3$  and  $m_2$  represent the third and the second moment about the mean, respectively (Ferguson, 1971). Table 14 lists the computed Chi-squares and the skewness measures, as well as the corresponding  $\bar{P}$  for variations in

Table 14. Chi-squares with corresponding degrees of freedom ( $\chi^2/df$ ) and measures of skewness (G) of lateral image position distributions for variations in interaural phase difference ( $\theta$ ), for the condition without standard. Data listed also include the corresponding  $\bar{P}$  values (in degrees). Letter L or R following each  $\bar{P}$  indicates image is located on either the left side or the right side of the center.

$\theta$ (in degrees)	HT			PT			
	$\chi^2/df$	G	$\bar{P}$	$\chi^2/df$	G	$\bar{P}$	
105	94.82/34	-0.1952	45.4-L	178.12/11	1.9817	79.5-L	
65	15.78/21	-0.3372	14.0-L	49.71/22	-0.6133	39.5-L	
45	15.93/10	0.0523	5.9-L	12.69/14	-0.3579	19.1-L	
Left Ear Leading	25	11.91/13	-0.3161	15.8-L	88.40/22	-0.9964	28.5-L
	20	25.27/14	-0.2997	13.1-L	21.62/ 8	-0.2964	9.7-L
	15	32.72/12	-0.1863	12.6-L	63.85/15	-0.7166	2.4-L
	10	39.39/15	-0.1961	14.2-L	19.49/16	-0.1787	14.6-L
	5	10.76/11	-0.2490	10.4-L	20.91/11	0.0031	3.1-L
	5	30.31/14	0.0573	8.5-R	58.40/16	-0.5877	1.0-R
	10	37.07/10	0.7895	9.7-R	37.78/11	0.3652	2.1-R
	15	13.76/12	0.0212	9.2-R	19.93/12	-0.2484	3.8-R
Right Ear Leading	20	20.55/12	-0.2251	11.3-R	32.33/ 9	1.2088	11.2-R
	25	49.94/13	0.5948	17.8-R	29.59/ 8	0.1911	3.3-R
	45	36.03/14	0.5770	19.3-R	39.84/26	0.1790	36.5-R
	65	19.94/18	0.0458	32.5-R	45.69/17	0.6669	28.2-R
	105	27.34/24	-0.0271	52.3-R	38.83/27	-0.1213	45.1-R

interaural phase difference ( $\theta$ ) over the two listeners for the condition without standard. Similarly, data for conditions with the left standard and the right standard are listed in Tables 15 and 16, respectively.

Again, as  $\sigma_P$  depended on  $\bar{P}$ , the shape of the distribution of  $P$  might also depend on  $\bar{P}$ , so the results of the measures of skewness ( $G$ ) were rearranged according to the order of  $\bar{P}$  (from the left to the right) over all three standard conditions. Such representations are listed in Table 17 for listener HT and Table 18 for listener PT. For each distribution, the significance of the Chi-square goodness of fit test for normality is indicated in both tables. For the total of 96 distributions (both listeners), 62 distributions are determined to be significantly non-normal (51 are significant at the 0.01 level, and the other 9 at the 0.05 level). (Note that 62 out of 96 is a highly significant binomial result for the type-one error rates selected.) It is clear that the working assumption of normality,  $N(\bar{P}, \sigma_P)$ , for  $P$  that was proposed by Domnitz and Colburn (1977) and predicted by the Stern and Colburn (1978) model has not been supported.

For the measures of skewness,  $G$ , ignoring a few exceptions, a pattern can be seen in both tables (17 and 18). For a better visual representation, data for  $G$  in the two tables were plotted as a function of  $\bar{P}$  in Figure 37. Generally, the  $P$  distribution appears more skewed towards the ipsilateral ear as  $\bar{P}$  moves away from or the center, but is least skewed for

Table 15. Chi-squares with corresponding degrees of freedom ( $\chi^2/df$ ) and measures of skewness (G) of lateral image position distributions for variations in interaural phase difference ( $\theta$ ), for the condition with left standard. Data listed also include the corresponding  $\bar{P}$  values (in degrees). Letter L or R following each  $\bar{P}$  indicates image is located on either the left side or the right side of the center.

$\theta$ (in degrees)	HT			PT			
	$\chi^2/df$	G	$\bar{P}$	$\chi^2/df$	G	$\bar{P}$	
105	49.60/20	-0.0531	27.0-R	74.76/14	-0.3427	2.3-L	
65	36.18/12	0.9231	3.8-R	222.03/21	0.9279	11.9-R	
45	25.56/11	0.4284	14.3-R	36.43/16	-0.0258	3.7-L	
Left Ear Leading	25	24.04/ 8	-0.3032	10.1-R	53.67/15	-0.0576	1.6-L
20	18.14/12	-0.0633	11.6-R	46.86/24	0.3012	19.7-R	
15	91.11/12	1.8360	15.3-R	138.79/25	0.8767	18.8-R	
10	20.50/12	0.0094	7.6-R	171.49/13	0.5327	6.1-R	
5	24.58/10	-0.1224	1.9-R	17.17/17	0.1582	25.0-R	
5	25.50/11	0.4014	14.3-R	19.78/22	-0.0103	31.2-R	
10	40.00/14	0.8461	15.7-R	37.53/19	0.4437	18.5-R	
15	31.24/24	-0.1639	40.6-R	44.62/15	-0.1755	26.8-R	
Right Ear Leading	20	27.57/23	-0.0052	45.5-R	26.29/14	-0.2590	18.1-R
25	34.43/21	0.2770	33.6-R	38.43/16	0.4879	23.7-R	
45	26.37/17	0.2955	27.6-R	63.54/22	-0.4490	61.1-R	
65	32.67/24	0.0048	60.8-R	13.39/18	-0.0541	28.3-R	
105	24.40/ 8	-0.5228	85.6-R	93.65/12	-2.1132	87.0-R	

Table 16. Chi-squares with corresponding degrees of freedom ( $\chi^2/df$ ) and measures of skewness (G) of lateral image position distributions for variations in interaural phase difference ( $\theta$ ), for the condition with right standard. Data listed also include the corresponding  $\bar{P}$  values (in degrees). Letter L or R following each  $\bar{P}$  indicates image is located on either the left side or the right side of the center.

$\theta$ (in degrees)	HT			PT			
	$\chi^2/df$	G	$\bar{P}$	$\chi^2/df$	G	$\bar{P}$	
105	102.41/16	0.7900	69.9-L	77.39/ 5	0.3983	84.0-L	
65	50.40/19	0.1923	66.7-L	38.76/19	-0.1804	62.0-L	
45	28.30/17	0.3269	64.1-L	91.31/16	0.1633	61.8-L	
Left Ear Leading	25	21.03/20	-0.1417	54.5-L	54.64/22	0.0158	41.9-L
20	24.21/24	0.3165	50.9-L	57.46/20	-0.0290	37.7-L	
15	20.11/20	0.2612	35.9-L	16.76/17	0.0520	33.6-L	
10	28.91/15	-0.3254	17.3-L	12.34/17	-0.0936	21.1-L	
5	37.25/12	-0.4380	13.0-L	42.11/16	-0.7036	25.6-L	
5	5.87/12	-0.0935	9.6-L	36.00/18	0.0324	13.8-L	
10	14.47/10	-0.1922	2.1-L	253.38/11	-1.2837	5.1-L	
15	29.65/15	-0.1242	18.9-L	12.64/15	-0.1393	31.8-L	
Right Ear Leading	20	24.25/20	-0.3623	26.4-L	20.25/18	-0.3280	30.7-L
25	16.30/12	-0.3308	10.9-L	26.50/18	-0.2161	43.9-L	
45	78.03/ 8	0.0413	1.9-R	10.45/11	-0.4728	13.0-L	
65	18.37/ 8	0.3566	5.3-R	76.10/ 8	2.6924	6.9-R	
105	64.47/22	0.9160	13.2-R	48.42/15	0.2799	5.6-R	

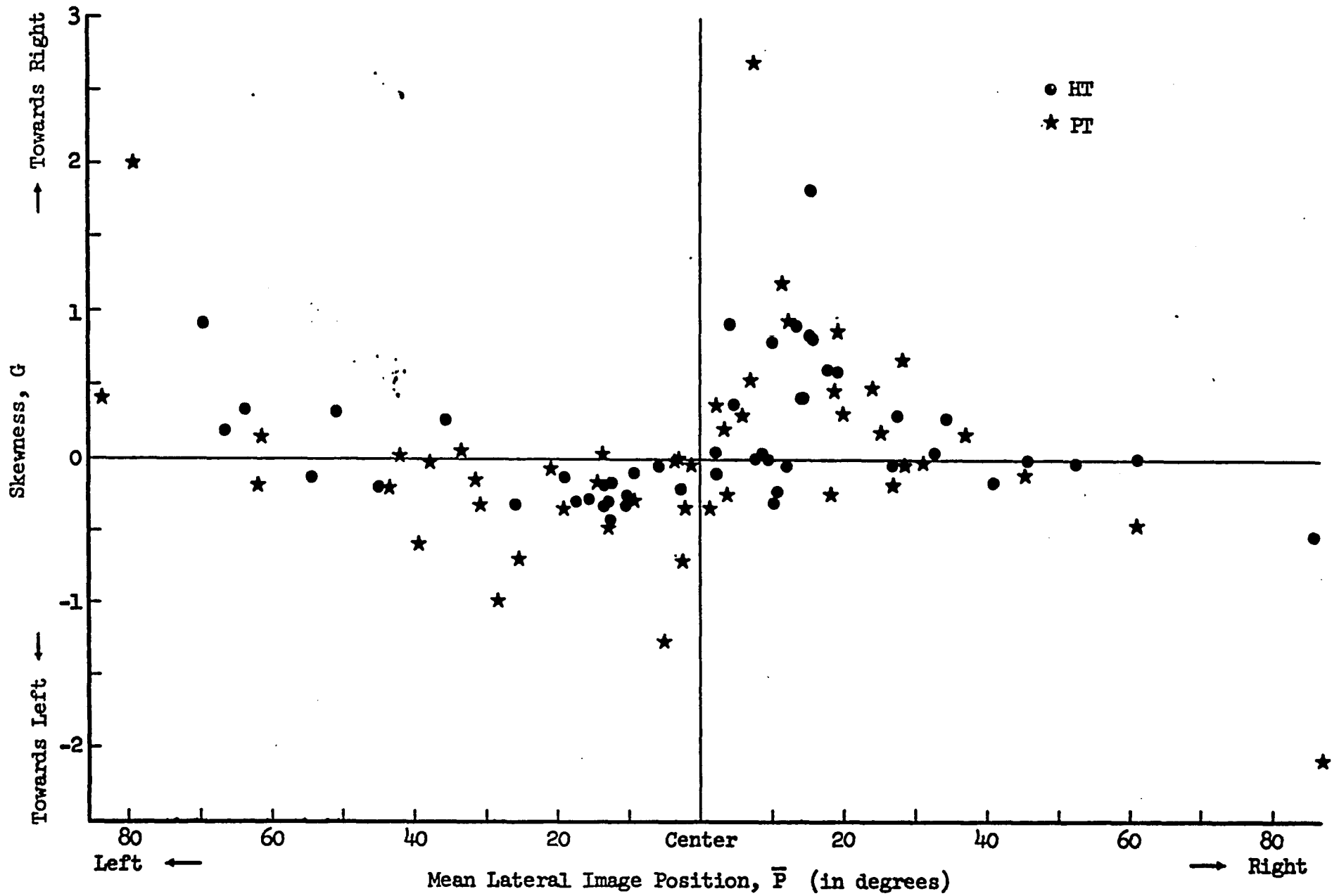
Table 17. Means ( $\bar{P}$ ) and corresponding measures of skewedness (G) of image position distributions for all stimulus conditions for listener HT. Data are listed in the order of  $\bar{P}$  and the letter L or R following each  $\bar{P}$  indicates  $\bar{P}$  is located on either the left or the right side of the center, accordingly. Results of Chi-square goodness of fit tests for normality are labeled as: \*\*\* - significant at .01 level, \*\* - significant at .05 level, and \* - significant at .10 level, all for a one-tailed type-one error rate.

$\bar{P}$	G		$\bar{P}$	G		$\bar{P}$	G	
69.9-L	0.7900	***	10.9-L	-0.3308		13.2-R	0.9106	***
66.7-L	0.1923	***	10.4-L	-0.2490		14.3-R	0.4284	***
64.1-L	0.3269	**	9.6-L	-0.0935		14.3-R	0.4014	***
54.5-L	-0.1417		5.9-L	0.0523		15.3-R	1.8360	***
50.9-L	0.3165		2.1-L	-0.1922		15.7-R	0.8461	***
45.4-L	-0.1952	***	1.9-R	0.0413	***	17.8-R	0.5948	***
35.9-L	0.2612		1.9-R	-0.1224	***	19.3-R	0.5770	***
26.4-L	-0.3623		3.8-R	0.9231	***	27.0-R	-0.0531	***
18.9-L	-0.1242	**	5.3-R	0.3566	**	27.6-R	0.2955	*
17.3-L	-0.3254	**	7.6-R	0.0094	*	32.5-R	0.0458	
15.8-L	-0.3161		8.5-R	0.0573	***	33.6-R	0.2770	**
14.2-L	-0.1961	***	9.2-R	0.0212		40.6-R	-0.1639	
14.0-L	-0.3372		9.7-R	0.7895	***	45.5-R	-0.0052	
13.1-L	-0.2997	**	10.1-R	-0.3032	***	52.3-R	-0.0271	
13.0-L	-0.4380	***	11.3-R	-0.2251	*	60.8-R	0.0048	
12.6-L	-0.1863	***	11.6-R	-0.0633		85.6-R	-0.5228	***

Table 18. Means ( $\bar{P}$ ) and corresponding measures of skewedness ( $G$ ) of image position distributions for all stimulus conditions for listener PT. Data are listed in the order of  $\bar{P}$  and the letter L or R following each  $\bar{P}$  indicates  $\bar{P}$  is located on either the left or the right side of the center, accordingly. Results of Chi-square goodness of fit tests for normality are labeled as: \*\*\* - significant at .01 level, \*\* - significant at .05 level, and \* - significant at .10 level, all for a one-tailed type-one error rate.

$\bar{P}$	$G$		$\bar{P}$	$G$		$\bar{P}$	$G$	
84.0-L	0.3983	***	13.8-L	0.0324	***	11.2-R	1.2088	***
79.5-L	1.9817	***	13.0-L	-0.4728		11.9-R	0.9279	***
62.0-L	-0.1804	***	9.7-L	-0.2964	***	18.1-R	-0.2590	**
61.8-L	0.1633	***	5.1-L	-1.2837	***	18.5-R	0.4437	***
43.9-L	-0.2161	*	3.7-L	-0.0258	***	18.8-R	0.8767	***
41.9-L	0.0158	***	3.1-L	0.0031	**	19.7-R	0.3012	***
39.5-L	-0.6133	***	2.4-L	-0.7166	***	23.7-R	0.4879	***
37.7-L	-0.0290	***	2.3-L	-0.3427	***	25.0-R	0.1582	
33.6-L	0.0520		1.6-L	-0.0576	***	26.8-R	-0.1755	***
31.8-L	-0.1393		-----			28.2-R	0.6669	***
30.7-L	-0.3280		1.0-R	-0.5877	***	28.3-R	-0.0541	
28.5-L	-0.9940	***	2.1-R	0.3652	***	31.2-R	-0.0103	
25.6-L	-0.7036	***	3.3-R	0.1911	***	36.5-R	0.1790	**
21.1-L	-0.0936		3.8-R	-0.2484	*	45.1-R	-0.1213	*
19.1-L	-0.3579		5.6-R	0.2799	***	61.1-R	-0.4490	***
14.6-L	-0.1787		6.1-R	0.5327	***	87.0-R	-2.1132	***
			6.9-R	2.6924	***			

Figure 37. Measure of skewedness ( $G$ ) as a function of mean lateral image position ( $\bar{P}$ ), in degrees. Data points include all stimulus conditions and two listeners.



$|\bar{P}| \approx 45^\circ$ . When  $\bar{P}$  moves laterally beyond  $\pm 60^\circ$ , the skewness changes direction, and the P distributions become skewed towards the center of the head. It seems then that there are actually three boundaries for P, one at the midline and the others at the limits of the two sides (ears).

From the data of this study it is now possible to predict interaural phase (time) jnd's by taking the underlying position that the jnd of  $\Delta\bar{P} \approx \sigma_P$ . Given a value of  $\theta$ , for each presentation of the stimulus the decision variable for lateral image position is presumably  $P(\theta)$ . The distribution of  $P(\theta)$  will be centered at  $\bar{P}$  and will have a variance of  $\sigma_P^2$ . Similarly, for another presentation,  $\theta + \Delta\theta$ , the distribution of P will be centered at  $\bar{P} + \Delta\bar{P}$ , but can be assumed to have nearly the same variance,  $\sigma_P^2$ , for sufficiently small  $\Delta\bar{P}$  (see Figure 36 for  $\theta = 5^\circ, 10^\circ, 15^\circ$ , and  $20^\circ$ ). (Note that for all stimulus conditions and the two listeners, the four variances for each set of distributions of the actual  $\theta_i$  were nearly the same. That also further justified the procedure used for collapsing each set of four local distributions into one. Those local  $\sigma_P$  data are not presented here.) For a two-interval forced choice task, the probability of a correct decision is easily determined under the assumption that the relevant distributions are normal. Even if the distributions of P are not normal, as already discussed, the relevant difference distributions are perfectly symmetrical and a normal curve approximation is

reasonable for the computation. The result is that the decisions will be approximately 75 per cent correct when  $\Delta\bar{P} \approx \sigma_P$ .

Consequently, to predict jnd's in the form of  $\Delta\theta$ , values of the jnd's  $\Delta\bar{P} = \sigma_P$  are first derived from the data for the 'no standard' condition in the range  $|\theta| \leq 105^\circ$ . These are implicitly valid only for the 50-msec tones at 250 Hz as used in this study. However, predictions for longer duration tones at various frequencies can be derived using the following considerations: (a) Supported by coincidence counter models (e.g., Jeffress, 1948; Stern and Colburn, 1978) which imply that position information is coded in the relative magnitude of the numbers of coincidence counts correlated with different subjective positions, the conclusion is drawn that  $\sigma_P$  should decrease as a function of duration in accordance with a square-root law. That is, if duration is multiplied by a factor of  $N$ , the variance of the coincidence counting mechanism is reduced by multiplying by  $1/N$ , as if the mechanism averages counts over  $N$  samples. The discrimination experiments considered here (Yost, 1974; Donnitz and Colburn, 1977) used 300-msec tones, leading to a correction factor of  $(6)^{-\frac{1}{2}}$  for  $\sigma_P$ . (b) Given the results of Yost (1974), it is clear that the critical variable for interaural time discrimination below about 1000 Hz is  $\theta$  (phase shift), not  $\tau$  (time delay). Yost's (1974) results show that  $\Delta\theta$  versus  $\theta$  functions are virtually superimposable for 250, 500, and 900 Hz. The average position functions reported by

Sayers (1964) for frequencies ranging from 200 to 1200 Hz are also clearly common functions of interaural phase-shift and not interaural time delay. Thus,  $\Delta\theta$  derived from  $\sigma_p/\sqrt{6}$ , and viewed as a function of  $\theta$ , is the desired result.

Next, the relationship between  $\Delta\bar{P}$  and  $\Delta\theta$  can be derived as follows. Assuming  $\bar{P}$  is linearly related to  $\theta$  as discussed before (see Figure 36), the regression line can be written as:

$$\bar{P} = m(\theta) + b \quad .$$

It is clear that the present study is a small range identification experiment and is similar to a discrimination experiment in the sense that the listener must make judgements based on closely spaced stimuli presented in random order within a block of trials. Since for all sets of four actual  $\theta_i$  (for a nominal interaural phase difference,  $\theta$ ), the relationship between  $\bar{P}(\theta_i)$  and  $\theta_i$  (for both listeners) was determined to be satisfactorily linear (see Results Section), and all local slopes for the sets of four  $\theta_i$  are significantly higher than the overall slope for  $\bar{P}(\theta)$  as discussed before, an appropriate prediction of  $\Delta\theta$  from  $\Delta\bar{P}$  would employ the local slope instead of the overall slope. That is, using

$$\bar{P} = m_i(\theta_i) + b_\theta \quad ,$$

then

$$\Delta\theta = (\Delta\bar{P}) / (m_\theta) \approx (\sigma_p) / (m_\theta)$$

where  $m_\theta$  is the local slope for each  $\theta$  (see Table 13). By using the data listed in Table 11 (averaged over the directions left and right as well as over the two listeners), the predicted  $\Delta\theta$

values were computed and are listed in Table 19. For comparison with Yost's (1974) data for interaural phase-shift jnds, the  $\Delta\theta$  values in Table 19 were then divided by  $\sqrt{6}$ , and the results are also listed in Table 19. Both the corrected jnd  $\Delta\theta$  values as derived from this study and the jnd  $\Delta\theta$  values reported by Yost (1974) (averaged over the directions left and right) are plotted as a function of interaural phase difference ( $\theta$ ) in Figure 38. From this comparison, it is quite clear (especially given the different subjects, different tasks, different laboratories, and the difficulties involved in obtaining the lateralization data) that the predicted (from this study) and the obtained (from Yost's study) jnd's agree remarkably well.

Considering only the global features of the  $\bar{P}$  scale, in Table 11, for the data without standard,  $\sigma_p$  is an increasing function of  $|\bar{P}|$  over the range of  $|\theta|$  studied, and increases by two to three times its value as  $|\theta|$  increases from  $5^\circ$  to  $105^\circ$ . Since the behavior of  $\sigma_p$  depends directly on  $\bar{P}$  instead of  $\theta$ , data listed in Table 11 are replotted with  $\sigma_p$  as a function of  $|\bar{P}|$  in Figure 39. A rough approximation to the behavior of  $\sigma_p$  is that  $\sigma_p$  is roughly constant for  $|\bar{P}| \leq 12^\circ$ , and increases linearly for  $|\bar{P}| > 12^\circ$ .

A phenomenon dependent upon  $\sigma_p$  that may be related to the general problem of stimulus duration and variability (as already discussed) is that of the subjective spread versus fusion (compactness) of the binaural image. In this study the choice

Table 19. Predicted interaural phase difference jnd's ( $\Delta\theta$ ), in degrees, for variations in (absolute) interaural phase difference ( $|\theta|$ ), in degrees. Data listed are those for the condition without standard. For a detailed explanation, see text.

$ \theta $	5	10	15	20	25	45	65	105
$m_\theta$	.987	.849	.796	.580	.955	.820	.887	.593
$\Delta P \approx \sigma_P$	5.9	5.9	5.5	5.0	8.3	8.6	9.6	14.5
$\Delta\theta$	6.0	7.0	6.9	8.6	8.7	10.5	10.8	24.5
$\Delta\theta/\sqrt{6}$	2.4	2.8	2.8	3.5	3.6	4.3	4.4	10.0

Figure 38. Comparison of interaural phase difference jnd between the predicted values in this study (●) and the study by Yost, 1974 (☆ for 250 Hz and ★ for 500 Hz tone bursts). For a detailed explanation, see text.

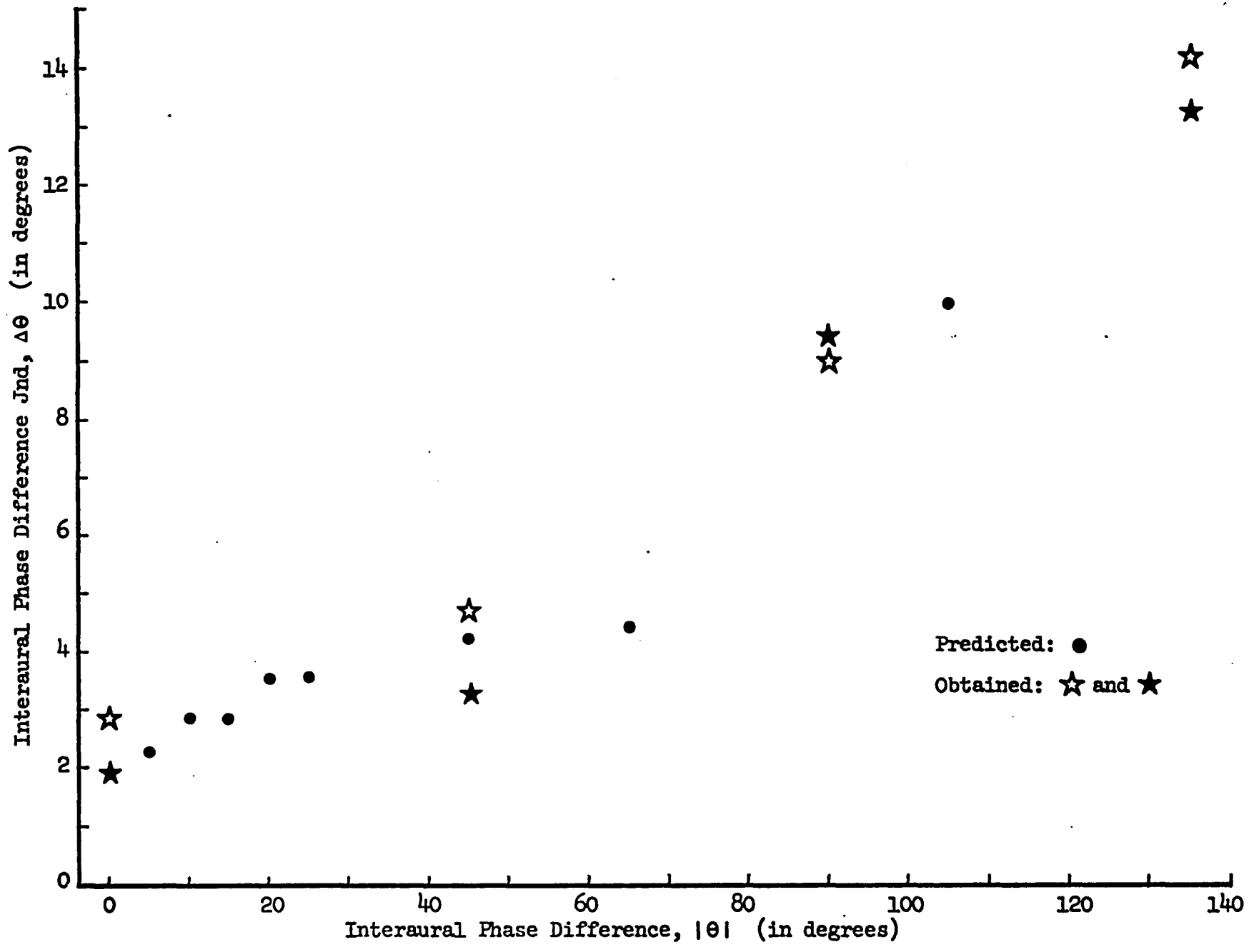
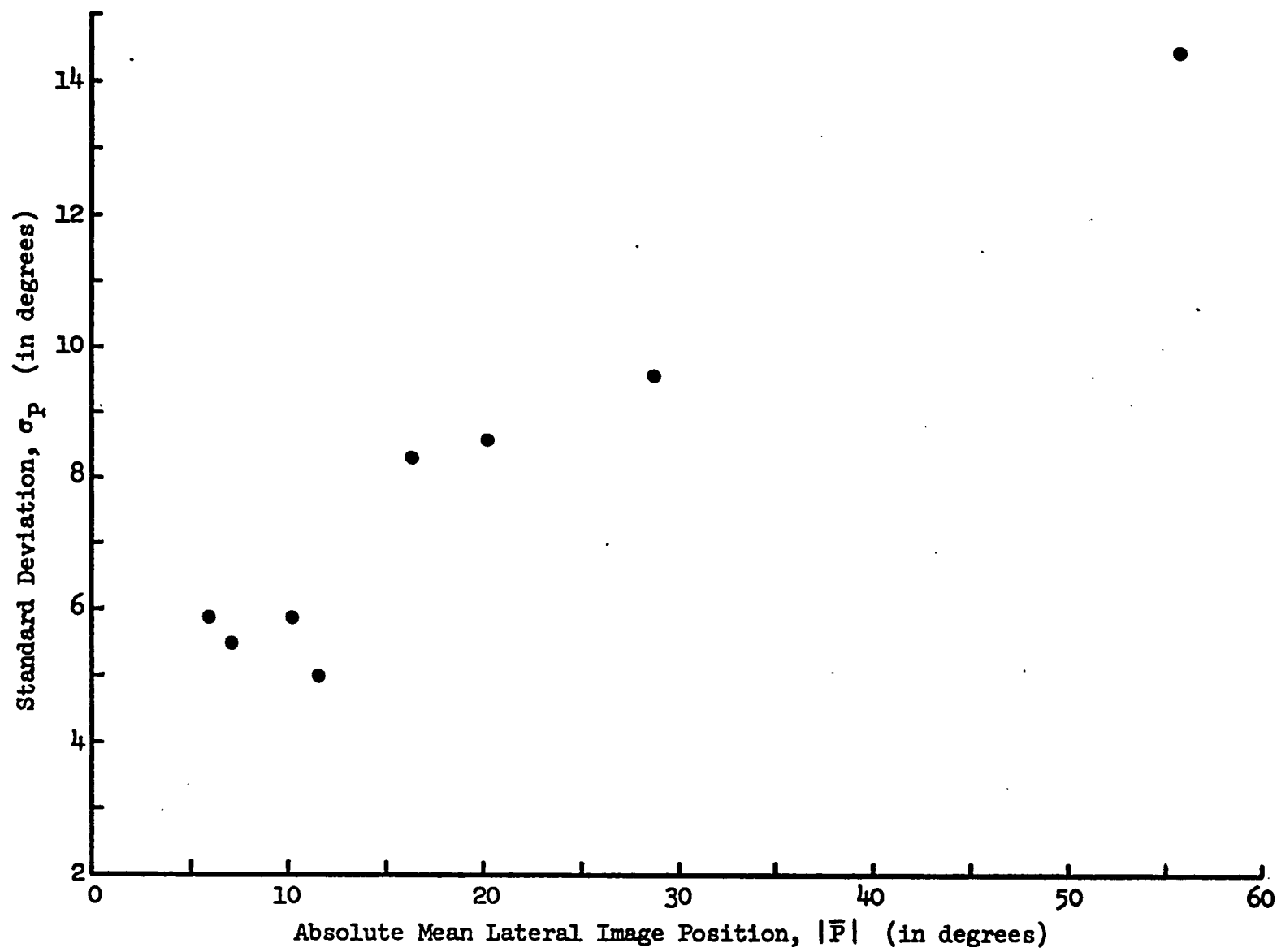


Figure 39. Standard deviation ( $\sigma_p$ ), in degrees, as a function of absolute mean lateral image position ( $|\bar{P}|$ ), in degrees. Data points are included only for the condition without standard.



of 50-msec signals followed pilot work in which the listeners were bothered by the difficulty of making position judgements with longer (i.e., 250 msec) tones. The longer tones generated images that were not well fused, but rather appeared to move, in contrast to the perceptions associated with the 50-msec tones eventually used. It is intuitively sensible that position variance would cause the listener to sense movement or multiple images for sufficiently long durations when the task is to study the sensation itself, even though interaural phase shift discrimination is improved due to the statistical advantage inherent in successive samples (as discussed earlier). Thus the variation of  $\sigma_p$  as  $|\bar{P}|$  increases from  $0^\circ$  is in agreement with the qualitative reports that the image is very well fused or compact when located at the center or fully lateralized at either side, but is diffuse or spread out when located about midway between the center and either side (Harris, 1960; Whitworth and Jeffress, 1961; Sayers, 1964; Sayers and Lynn, 1968). Furthermore, the possibility of distinct multiple images may have its basis in  $\sigma_p$ , as suggested by the report of dual and spatially separated images in the Sayers' (1964) paper, for large  $\theta$  values. Perhaps this is related to the question of the existence of separate time and intensity images (e.g., Whitworth and Jeffress, 1961; Hafter and Jeffress, 1968).

The results of this study are only indirectly relevant to questions of interaural intensity differences and time-intensity

trading. Domnitz and Colburn (1977) and Stern and Colburn (1978) used an interaural intensity ratio ( $\Delta I$ ) pointer to map the loci of images of interaural phase (time) shifts ( $\theta$  or  $\tau$ ). The explicit underlying assumption was that the listener matches the subjective positions of the 'phase' image and the 'intensity' image, and that position is a monotonic function of the corresponding interaural difference. The procedure thus defines one form of time-intensity trading measurement. However, there is ample evidence that time and intensity differences do not trade completely (e.g., Hafter and Carrier, 1972). In using their model to describe such matching results with position defined in decibels of interaural intensity shift, Stern and Colburn found both mean position (data and theory) and position variance (theory only) functions of interaural phase shift that are similar in form to the  $\bar{P}(\theta)$  and  $\sigma_p(\theta)$  results of this study. However, no further information about the P scale could be deduced. It is possible, given the limits and qualifications concerning time-intensity trading (and the related latency hypothesis; see Introduction), that the transforms  $P(\theta)$  and  $P(\Delta I)$  represent different subjective position scales. That is also suggested by the argument for separate 'time' and 'intensity' images in some reports (e.g., Whitworth and Jeffress, 1961; Hafter and Jeffress, 1968). Yost (1973) reported measurements of  $P(\Delta I)$  and  $P(\theta)$  for one subject using his 21 categories scale. Those  $P(\theta)$  results were discussed above in

comparison to this study, and his  $P(\Delta I)$  results are subject to the same procedural limitations. Thus, it would be warranted in future work for the higher resolution technique of the present study to be applied to the determination of the properties of the subjective position scale derived from variation of interaural intensity differences.

Since the introduction of an interaural intensity difference moves the subjective image towards the ear of higher intensity, one possible explanation for the lateralization shift produced by the standard in this study is that it is due to an effective interaural intensity shift. In other words, the standard may act as a masker for the test stimulus at the ipsilateral ear, reducing its effective intensity or loudness, and consequently, the image will be displaced towards the contralateral ear. However, the amount of interaural intensity difference needed to produce a given lateral shift of an image for a binaural stimulus with a given interaural phase shift can be estimated from other work. In order to do this, the results for  $\bar{P}(|\theta|)$  with no standard of this study were superimposed on a graph of the Domnitz and Colburn (1977) results for intensity pointer settings (in dB) matched in subjective position to the interaural time- and amplitude-shifted test stimulus (both pointer and test at 500 Hz). The Domnitz and Colburn data for  $\pm 3$  dB of an interaural amplitude shift of the test stimulus and the neighboring Stern and Colburn theoretical curve for a 0 dB interaural

amplitude shift of the test stimulus were plotted.  $\theta$  was used for the common abscissa and the ordinates were adjusted to achieve the best match between the two empirical studies, as shown in Figure 40. Given the many differences between the studies, the agreement is very good and the relative scale adjustment reveals the transform from intensity pointer setting in decibels (Domnitz and Colburn) to lateral position setting in degrees (this study) to be roughly a simple trade of 2.75 degree/dB. The next step involves the monaural standard data. The results for the left monaural standard and the right monaural standard with the ipsilateral ear leading in phase were averaged for common  $|\theta|$ . Then the remaining two sets of monaural standard results, with the contralateral ear leading in phase, were also averaged for common  $|\theta|$ . Redefining the  $\theta$  axis in terms of whether the leading ear was ipsilateral or contralateral to the standard, the results are plotted in Figure 41 along with the data that Domnitz and Colburn reported for test stimuli with interaural amplitude ratios of 3 dB and 9 dB. Figure 41 shows clearly that a value of  $\Delta I$  of from 7 to 9 dB would be required to produce the position shifts found with the monaural standard.

Available evidence from forward masking work indicates that such a shift is much too large to be expected from the 50-msec standard and 500-msec forward masking interval of this study. For instance, a 1000-Hz 500-msec masking tone produces no more than 2 dB of masking of a 20-msec tone of the same

Figure 40. Comparison of lateralization data between this study (●) for no standard and the study by Domnitz and Colburn, 1977 (☆ for  $\Delta I = 3$  dB and ★ for  $\Delta I = -3$  dB). The smooth theoretical curve is derived by Stern and Colburn (1978) for  $\Delta I = 0$  dB. For a detailed explanation, see text.

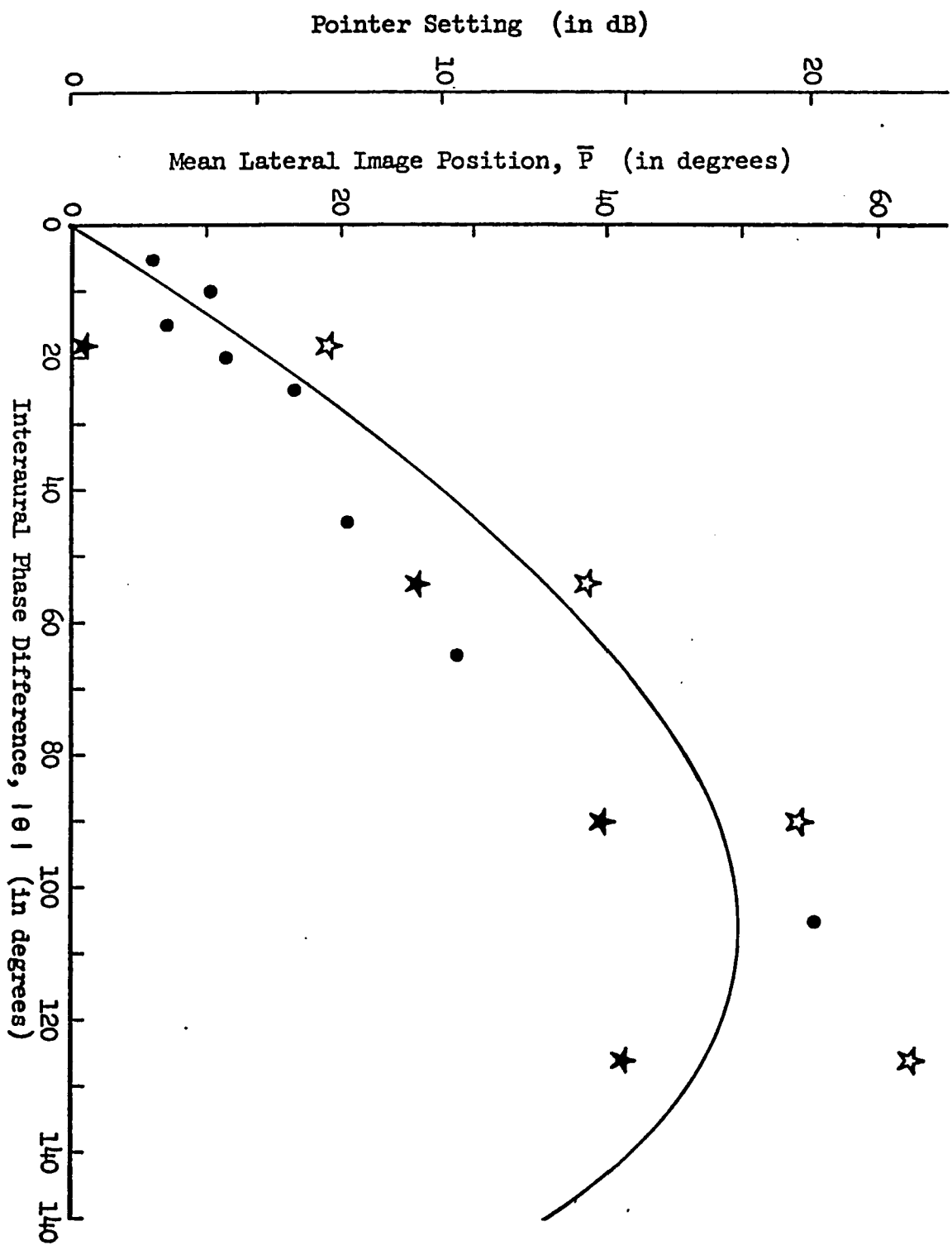


Figure 41. Comparison of lateralization data between this study (●) for monaural standards and the study by Domnitz and Colburn, 1977 (☆ for  $\Delta I = 9$  dB and ★ for  $\Delta I = 3$  dB). For a detailed explanation, see text.

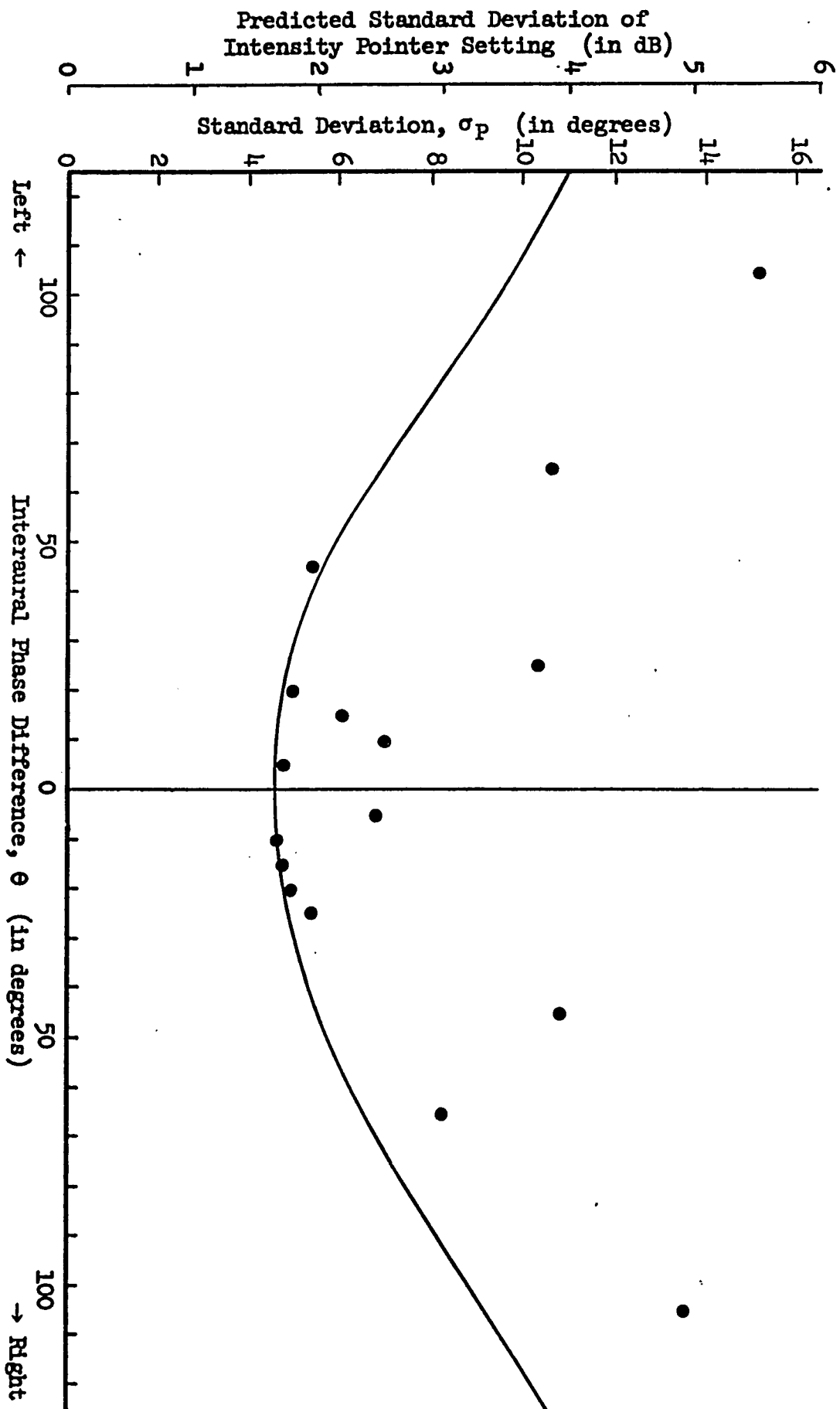


frequency when they are separated by 500 msec (Figure 22 of Zwisllocki, 1978). The loudness shift for a suprathreshold stimulus in a comparable experimental paradigm would perhaps be more relevant information. The available evidence (Scharf, 1978) is that there would be no loudness shift in such a case.

Having derived a transformation between the subjective position scale of this study and the intensity pointer scale of Domnitz and Colburn (1977) and Stern and Colburn (1978), it is instructive to examine the relationship between  $\sigma_p(\theta)$  of this study and the standard deviations of their intensity pointer settings. There are only predicted values for their standard deviation, based on the Stern and Colburn theoretical curves for mean pointer  $\Delta I$  (i.e., they did not report any real listener data on variability). Thus, Figure 42 displays the no standard  $\sigma_p$  results of this study along with the comparable theoretical standard deviation curve of Stern and Colburn (for a 0 dB interaural intensity ratio test stimulus). The results compare quite well, especially near the midline. The fact that the Stern and Colburn predicted curve is lower on the average than the  $\sigma_p$  results is readily explained using arguments presented earlier in the discussions of the results of Yost (1973) and Yost (1974), since Domnitz and Colburn used 500-msec stimuli in a paradigm allowing the listener to listen repeatedly before making a judgement.

Returning to the problem of the standard, binaural image

Figure 42. Comparison of standard deviation of lateral image position judgements between the direct measurements in this study (●) for no standard and the predicted theoretical curve derived by Stern and Colburn (1978) for  $\Delta I = 0$  dB. For a detailed explanation, see text.



movement similar to that produced by the standard is also produced on a much longer time scale (of seconds) in the 'moving phantom' adaptation technique (Wright, 1960). The possibility that a similar adaptation is a consequence of the repetitive (trial after trial) presentation of the 50-msec standard throughout a block of trials in this study is rendered implausible by the control analysis. That showed no difference for the effects of the standard between the first third and the last third of a block of trials.

No matter how the standard effect is mediated, the 500-msec standard-test interval dictates a central neural process. It is possible that the result of the process feeds back to modify the properties of the peripheral binaural system. Nevertheless, in spite of the agreement of the intensity pointer results and the results of this study as discussed above, the monaural standard results are strong evidence against the validity of the structural details of the peripherally based model put forth by Stern and Colburn (1978) as well as other models based primarily on cross-correlation-like processing of the binaural inputs. The model specifically fixes the distribution of internal interaural delays for fiber pairs that feed the coincidence counters and determine  $\bar{P}(\theta)$ . It also specifically accounts for  $\sigma_p$  entirely in terms of peripherally (auditory nerve) generated Poisson noise. The noise at the output of the coincidence detector is also considered to be Poisson (by

assuming that the time window over which coincidences are determined is sufficiently small and that there is negligible probability that an event on one fiber of a pair will coincide with more than one event on the other). Thus, the model ties the statistics of  $P$  to internal delay and does not allow for the possibility of the standard effect reported in this study. As a further point, the Poisson distribution approaches normality rapidly as the mean number of counts increases, so that the model is also not compatible with the finding that most of the distributions of  $P$  differ significantly from normality. Even if the results of distribution shape are considered weak, the main effects of the standard (the shift of  $\bar{P}$  and the fact that  $\sigma_P$  is function of  $\bar{P}$  and not  $\theta$ ) clearly support the conclusion that neither lateralization space nor its statistics are fixed by properties of the peripheral binaural system.

Incidentally, if the standard effect were to be viewed as equivalent to an interaural intensity shift, it would be an empirical contradiction to the predictions of the Stern and Colburn (1978) model. That is, the data show  $\sigma_P$  to be consistently minimal around  $\bar{P} = 0^\circ$ , which corresponds to  $\theta$  and effective  $\Delta I$  being in opposition (i.e., a left ear standard makes the right ear signal effectively more intense, and the left ear signal must be leading in phase to yield  $\bar{P} = 0^\circ$ ). However, the Stern and Colburn model shows that as  $\Delta I$  increases, the value of  $\theta$  for which subjective position is nearest the midline and the value

of  $\theta$  for which the predicted variance is minimal are of opposite sign (i.e., minimum  $\sigma_p$  moves away from  $\bar{P} = \theta$  as  $\Delta I$  increases).

One very important consideration is mandated by the finding of the standard effect. Many of the studies of binaural lateralization and binaural hearing in general have been conducted using paradigms where successive stimuli are presented with time intervals of the order of no more than 500 msec. This is true for the position matching studies of Domnitz and Colburn (1977) and the discrimination studies of Yost (1974) and Domnitz and Colburn (1977). Wherein these studies were designed to evaluate properties of binaural hearing based on subjective lateralization, they may be contaminated. That is, the results of such studies may be quantitatively affected by the interaction of temporally neighboring stimuli, such as in the case for the monaural standard and binaural test tones of this study.

Eventually, the results of this study may be best understood in relation to general contextual effects in perception. At this time, interpretation of the standard effect demonstrated in this study is necessarily limited to the elimination of the usual masking or adaptation effects that are well known in psychoacoustics, based on the duration of the interstimulus interval and the magnitude of the effect. Proper interpretation of the phenomenon clearly requires further study of its quantitative properties. The relation between the standard effect and the

small-range effect seen in the local slopes of  $\bar{P}(\theta_1)$  was previously discussed, and both appear similar to range effects in other perceptual situations. In fact, the general theory of intensity resolution introduced by Durlach and Braida (1969), which predicts an intensity range effect (due to the growth in memory variance with an increase in stimulus range), involves a formalization of the adaptation-level theory of Helson (1964). Such range effects are discussed by Parducci (1974) in a framework also related to Helson's adaptation-level theory. Range effects are found with stimuli and experimental paradigms quite different from the binaural tones and lateralization task of this study (e.g., rating the sizes of squares or making comparative judgements of weights). Parducci discusses range effects in category scaling and magnitude estimation, where the slope of the function relating mean response value to stimulus value varies inversely with the range of values in the set presented for judgement. This appears related to the general finding of increased discriminability amongst a pair of stimuli as the range of contextual stimuli presented decreases. Furthermore, discriminability between physical stimuli is reportedly greater when those stimuli are closer to an endpoint of the range of contextual stimuli. Processes responsible for these generalizations may also be operating in this study in the small-range effect of the local slopes of the  $\bar{P}(\theta_1)$ , and also the decrease in  $\sigma_p$  and increase in skewness near the boundaries

of the range of lateralization responses (with the interesting implication that the center of lateralization space may also function as a boundary).

Most important may be the (vague) concept of 'anchoring' as summarized by Parducci (1974), where a stimulus (the anchor) is introduced whose value is either higher or lower (i.e., more extreme) than any in the set originally presented for judgement. In effect, this extends the stimulus range. Consequently, the subject must stretch his/her original subjective scale to include the new stimulus, which would shift the judgements of the original stimuli away from that of the anchor. The standard effect seen in this study of binaural lateralization conforms to this general description of anchoring, and this implies again that the underlying explanation is of the nature of higher cognitive functioning, and not peripheral auditory physiology. Once again, this emphasis on more 'central' processes is very strongly implied by the clear dependency of  $\sigma_p$  on  $\bar{P}$  (rather than  $\theta$ ). Note that a literature search revealed no comparable study of the variability of subjective judgements in relation to either the general range effect or anchoring.

To the extent that the lateralization standard effect is explicable in the same way as the many other experimental results showing range effects, it certainly demands a major qualitative change in the lines of thought that binaural theorists have been following regarding the relationship between the auditory system,

subjective binaural space, and cognitive processes involving memory and comparative judgement.

As a final evaluation of the results of this dissertation, it is clear that the position judgement and data analysis procedures employed have provided new quantitative results that (a) appear to be a reliable and valid representation of the statistical properties of lateralization space, and (b) should be of importance for future advancements in the understanding of binaural hearing.

## APPENDIX

The following 8 figures, Figures A1 - A8, show selected histograms derived from the data base of this study (and using an interval width of  $2^\circ$ ) to illustrate statistical features characterizing the results. Two experimental conditions (out of the 48) were selected for each of the two listeners. In each of those four cases, the four local  $P(\theta_i)$  distributions and the corresponding  $P(\theta)$  distribution derived from them are presented. (Note that there are a total of 384 local  $P(\theta_i)$  distributions and an additional 96 combined  $P(\theta)$  distributions for the entire study.)

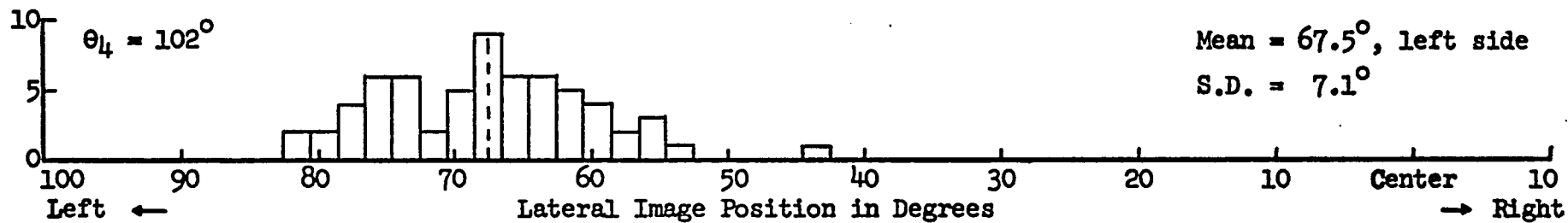
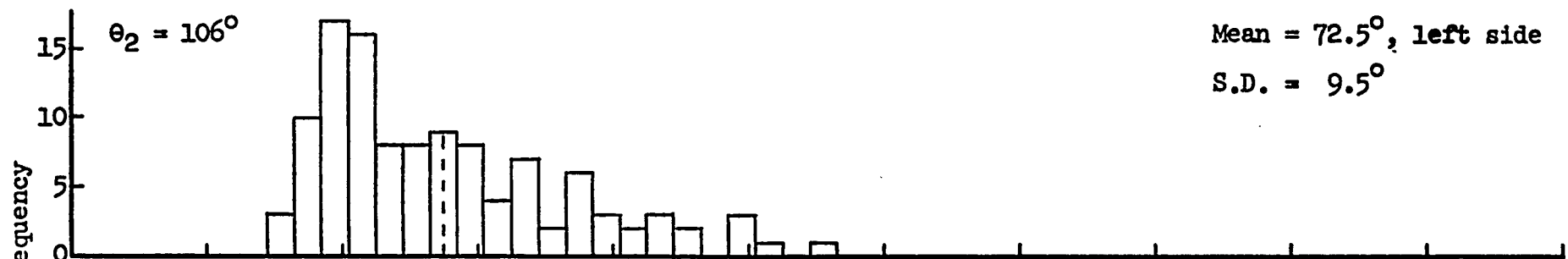
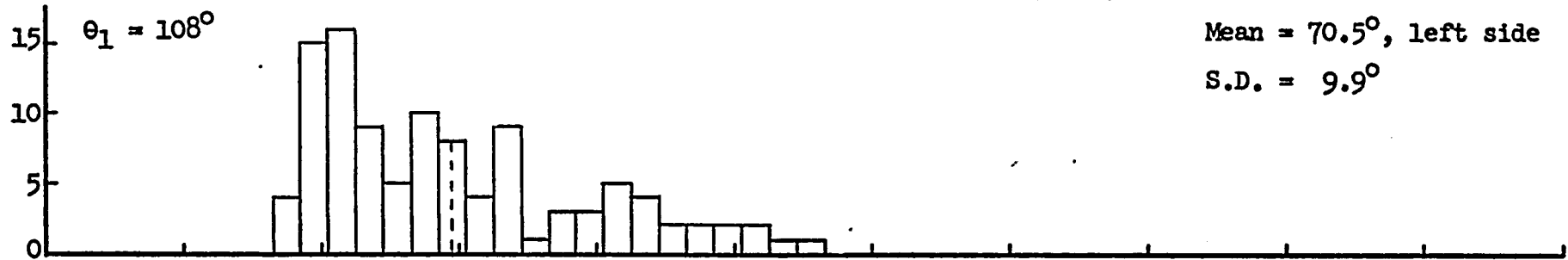
Figures A1 - A8. Selected sample histograms for either the four local  $P(\theta_i)$  distributions or the corresponding  $P(\theta)$  distribution derived for the data base of this study to illustrate statistical features characterizing the results. The notations used in these 8 Figures are same as those in the text.

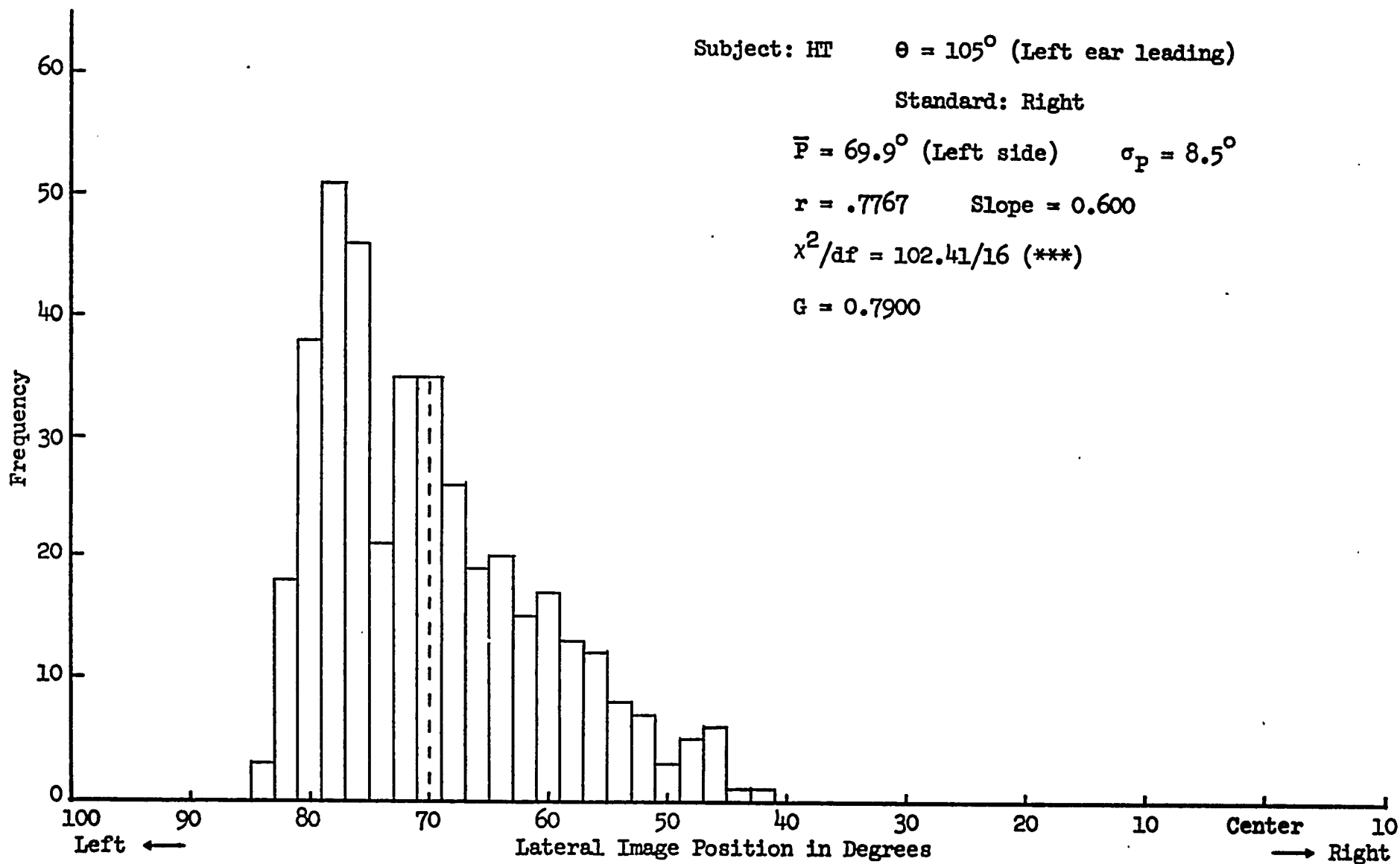
Subject: HT

$\theta = 105^\circ$  (Left ear leading)

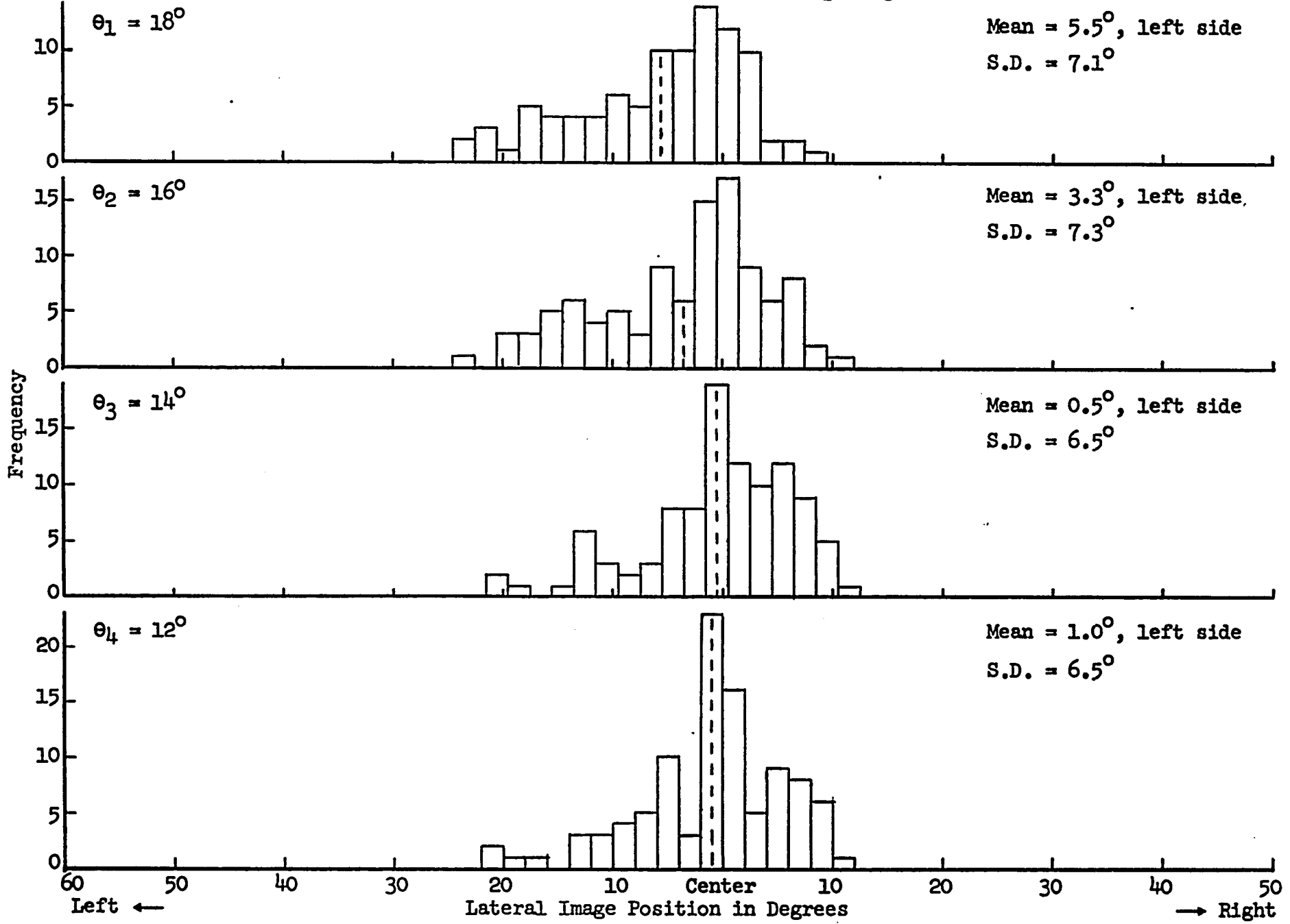
Standard: Right

Spacing:  $2^\circ$





Subject: PT     $\theta = 15^\circ$  (Left ear leading)    Standard: None    Spacing:  $2^\circ$



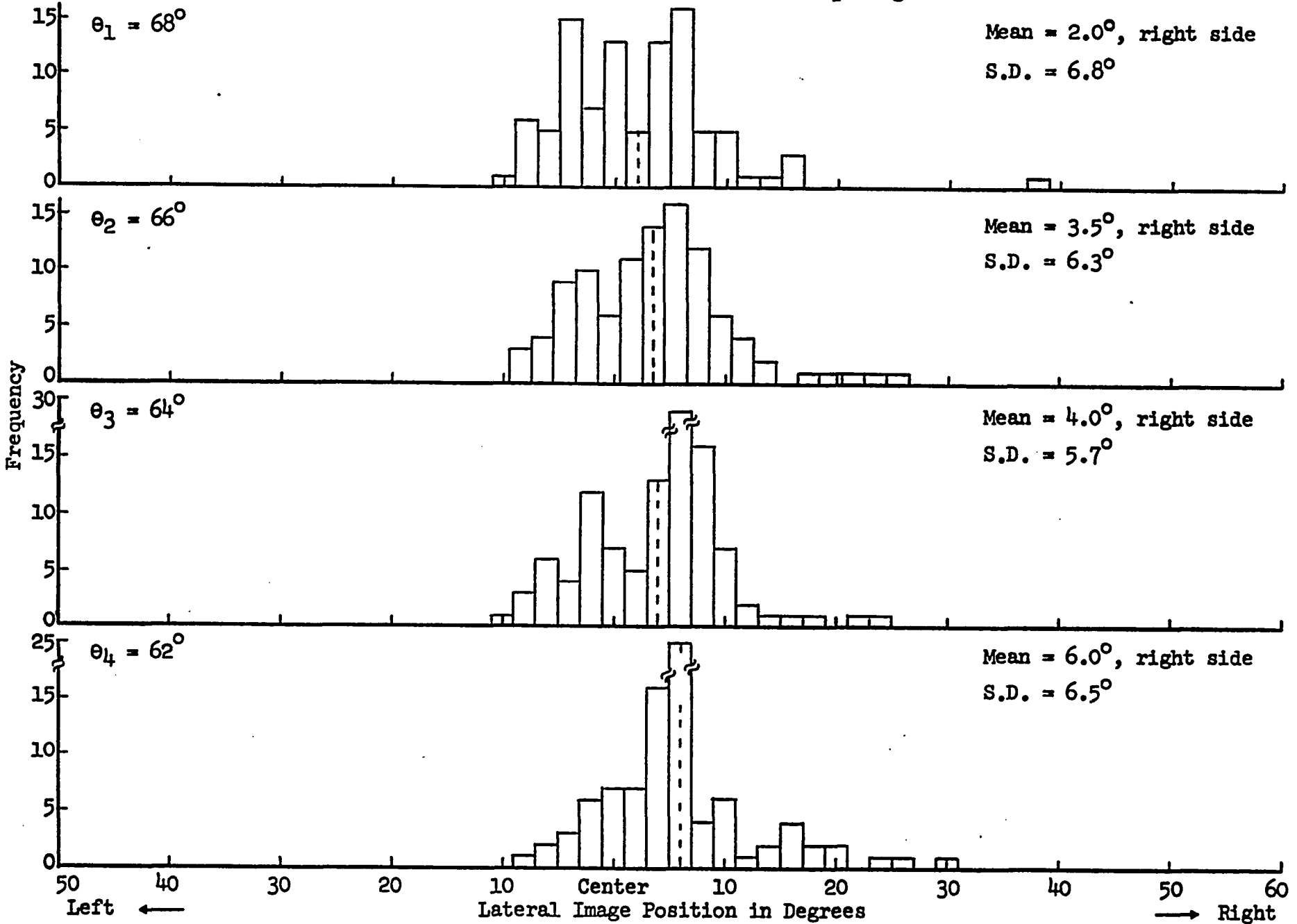


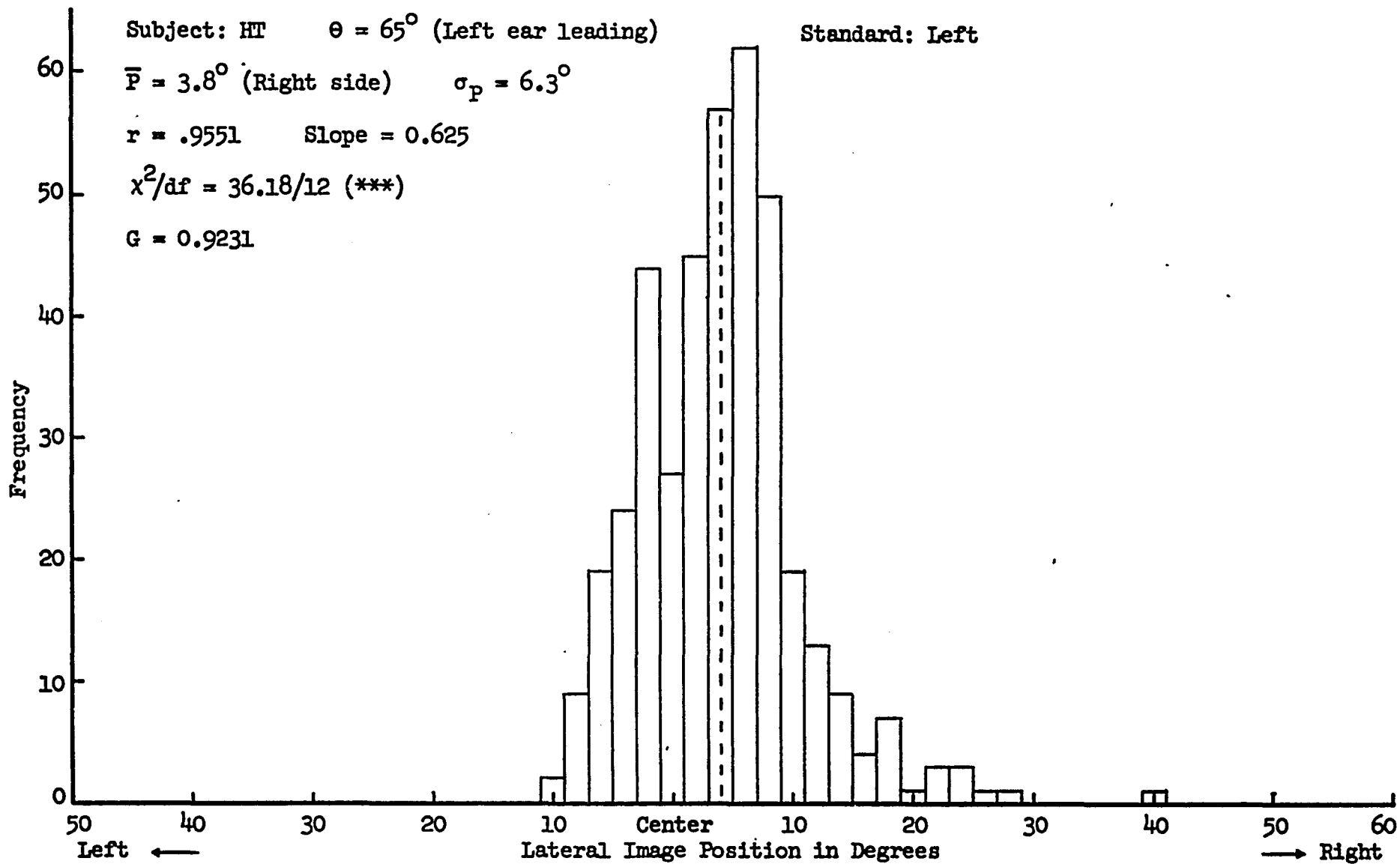
Subject: HT

$\theta = 65^\circ$  (Left ear leading)

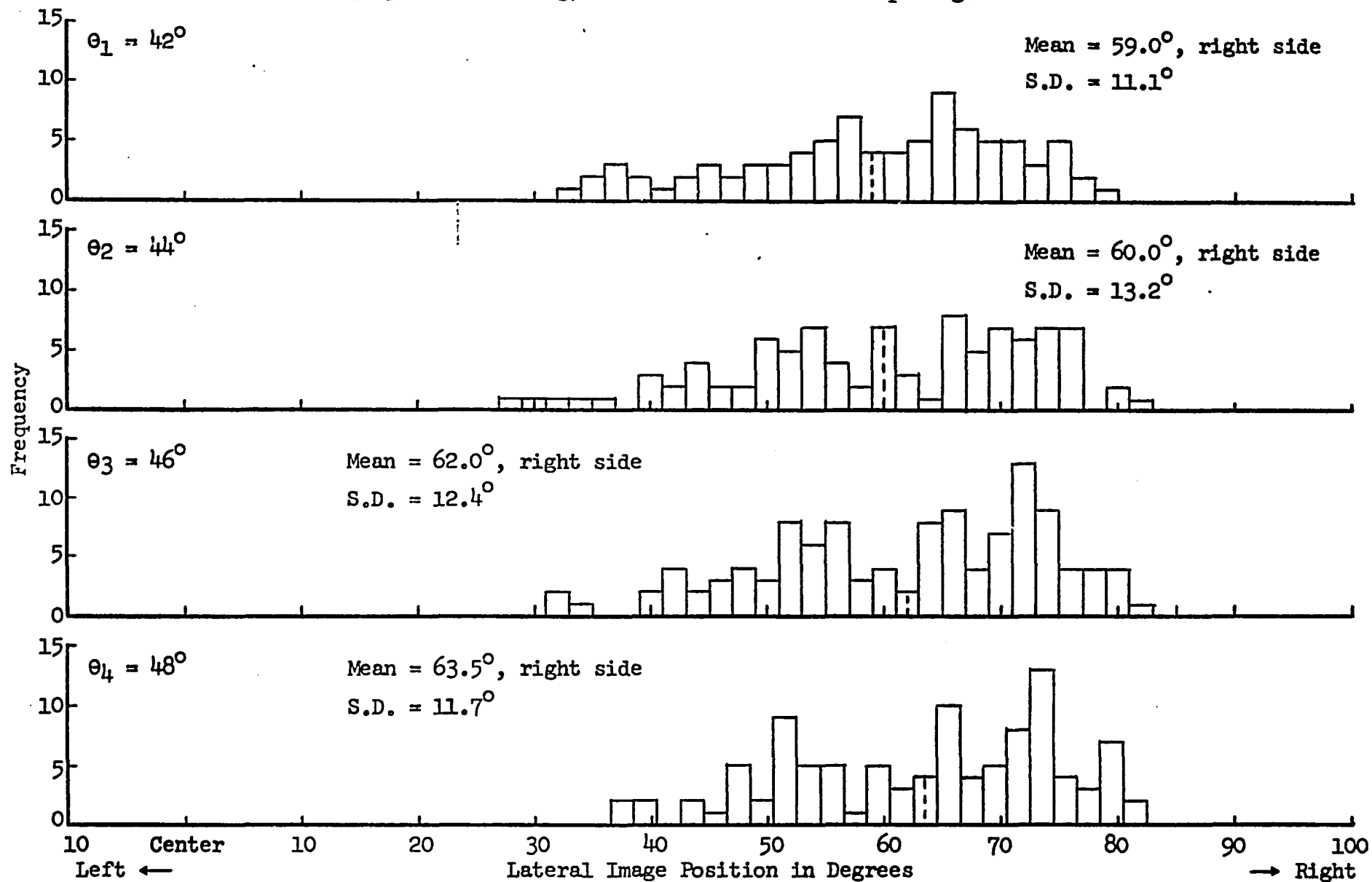
Standard: Left

Spacing:  $2^\circ$





Subject: PT     $\theta = 45^\circ$  (Right ear leading)    Standard: Left    Spacing:  $2^\circ$



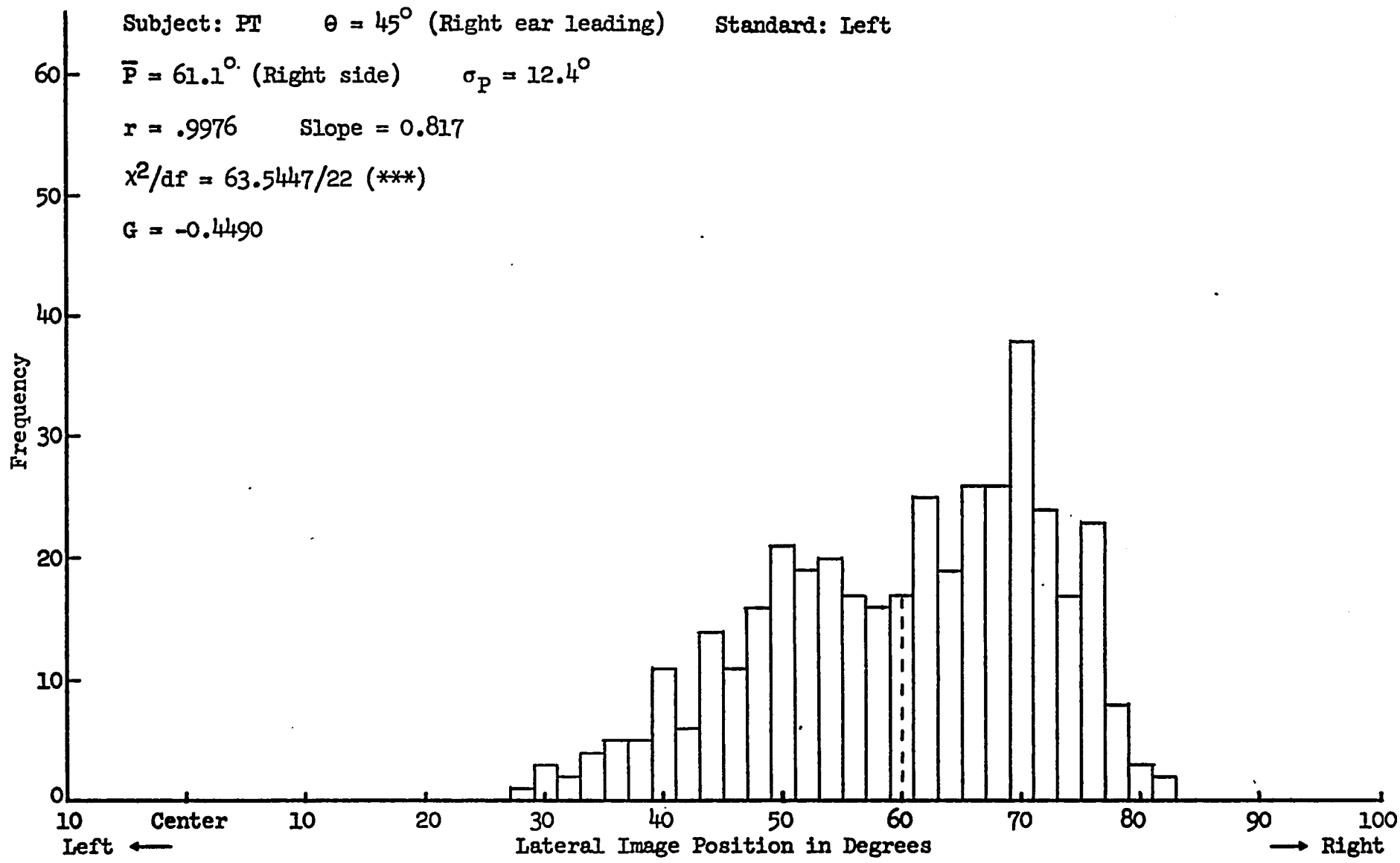
Subject: PT     $\theta = 45^\circ$  (Right ear leading)    Standard: Left

60     $\bar{P} = 61.1^\circ$  (Right side)     $\sigma_P = 12.4^\circ$

$r = .9976$     Slope = 0.817

$\chi^2/df = 63.5447/22$  (\*\*\*)

$G = -0.4490$



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