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The Influence of Interaural Phase on Interaural Summation and Inhibition*

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The difference between the binaural and monaural thresholds varies within fairly large limits. Although this binaural-monaural difference does not vary as a function of frequency when pure-tone thresholds are measured in the quiet, the difference does vary with frequency when pure tones are presented against a background of noise. *Binaural summation*, a term which has been used in the past to refer to the phenomenon in which the binaural threshold is lower than the monaural, obtains for masked thresholds only when the phase angles between the the two earphones are opposite for the tones and the noise. If the tones and the noise have the same interaural phase angle the binaural threshold is higher than the monaural. This phenomenon, called *interaural inhibition*, as well as its antipode, *interaural summation*, is most marked at low frequencies and increases as the intensity of the masking noise is increased. The discussion considers some implications of these findings for the theory of masking and of interaural summation.

IT has been shown in a previous experiment[1] that under certain experimental conditions the binaural threshold may be higher than the monaural. This observation led to the notion that there is some kind of inhibition of one ear on the other. This interaural inhibition can be shown most clearly when a tone of low frequency is masked by intense noise. It is now in order to fix this phenomenon with respect to the parameters that seem most intimately to determine it.

Recently, Licklider[2] has reported observations on the intelligibility of speech that reveal further evidence for interaural inhibition. Using fixed levels of speech and of noise, Licklider measured the intelligibility of speech presented binaurally under each of six interaural phase relations. He found that intelligibility was higher when the speech was in phase and the noise was out of phase[3] in the two earphones or when the speech was out of phase and the noise was in phase (antiphasic conditions) than when both the speech and noise were either in or out of phase (homophasic conditions). The intelligibility of speech that was masked by binaural noise from two independent sources, one for each ear (heterophasic conditions), was intermediate between the respective intelligibilities for the homophasic and antiphasic conditions. Licklider showed further that intelligibility under binaural homophasic conditions was lower than for monaural listening, and that intelligibility under binaural antiphasic conditions was higher than for monaural listening. His results under homophasic conditions are in complete agreement with the results on speech intelligibility reported previously by Hirsch.[1] His other results lend support to the notion that interaural inhibition might well be tied up with the interaural phase relations of the stimulus, of the noise, or of both. Although none of the present work is concerned with the intelligibility of speech, the data obtained from observations on pure tones, especially those of low frequency, support Licklider's results.

The present experiment has been designed to investigate interaural summation and inhibition as they relate to the following:

1. Phase relations between the two earphones of the tone and of the noise.
2. Frequency of the stimulus being masked by an intense noise.
3. Intensity of the noise used to mask a pure tone that is clearly "inhibitable."
4. Interaural phase angle of a tone of low frequency which is masked by a noise whose interaural phase angle is fixed.

* This research has been carried out under Contract N5ori-76 between Harvard University and the Office of Naval Research. Report PNR-51.

[1] I. J. Hirsh, "Binaural summation and interaural inhibition as a function of the level of masking noise," Am. J. Psychol. (in press).

[2] J. C. R. Licklider, "The influence of interaural phase relations upon the masking of speech by white noise," J. Acous. Soc. Am. **20**, 150 (1948).

[3] In Licklider's experiment, as well as in the present experiment, "noise out of phase" refers to the condition in which both earphones are fed by noise from a common source and the leads to one of the earphones are reversed.

APPARATUS AND PROCEDURE

A schematic block diagram of the equipment is presented in Fig. 1. The oscillator supplied pure tones which were fed to two separate channels, each one of which fed one earphone of a headset. The electronic switch was used to interrupt the pure tones without producing transients. The tone was on for one second and off for three seconds. The white noise had a continuous spectrum which was flat to 7000 c.p.s. The noise was supplied to both earphones throughout the entire experiment.

Each of three observers was provided with an attenuator by means of which he could vary the intensity of the pure tone. Transformers and resistive networks provided a means of reversing the phase relation between the pure tones in each channel. In conjunction with this reversing circuit, a double-pole, double-throw, reversing switch, connected to the left earphone, enabled the experimenter to use four combinations of interaural phase for binaural listening, and two for monaural listening. These six experimental conditions were as follows:

1. Tone—monaural; noise—binaural, in phase.
2. Tone—monaural; noise—binaural, out of phase.
3. Tone—binaural, in phase; noise—binaural, in phase.
4. Tone—binaural, out of phase; noise—binaural out of phase.
5. Tone—binaural, in phase; noise—binaural, out of phase.
6. Tone—binaural, out of phase; noise–binaural in phase.

According to Licklider's terminology, conditions 3 and 4 are homophasic while conditions 5 and 6 are antiphasic. Thus, homophasic conditions are those in which the noise and the tone have the same interaural phase relation. Under antiphasic conditions, the tone and noise have opposite interaural phase relations.

In each experimental session, 40 thresholds were measured. Five thresholds were obtained for each of the six experimental conditions. (This turns out to be 40 instead of 30 because 10 thresholds were obtained for each monaural condition—five for each ear.) Each experimental session, then, was run for a single frequency of the tone and a single intensity of the noise.

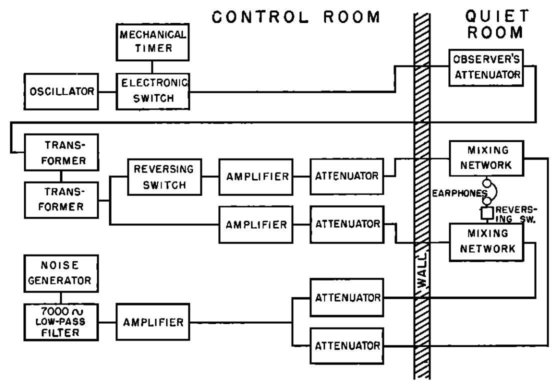

FIG. 1. Block diagram of equipment used to measure binaural and monaural masked thresholds for pure tones under various conditions of interaural phase.

The procedure of "equating" the two ears[1, 4] was omitted from this experiment for two reasons. First, since not only the binaural thresholds, but also the monaural thresholds, turned out to be affected by the interaural phase relation of the noise, it would have been extremely complicated and difficult to decide which monaural thresholds to equate for each of the four interaural phase conditions of binaural listening. Second, since all of the thresholds measured in this experiment were masked thresholds in which the crucial factor is the signal-to-noise ratio rather than the absolute intensity of the tone, there was little difference between the thresholds (intensity of the tone) of the right and left ears of the three observers used. The monaural thresholds which are reported are the average monaural thresholds.

The order of experimentation is most clearly shown by a division of the present experiment into three sub-experiments:

1. With a fixed intensity of noise in both phones, the monaural and binaural thresholds for the six interaural phase conditions were obtained for six frequencies. Each of the frequencies was tested on a different day for each observer and the order of frequencies was different for each observer.

2. With a constant frequency of the tone, thresholds under these same six conditions were obtained in five different intensities of noise. Each of the intensities of noise was used on a different day for each observer and the order in

[4] W. A. Shaw, E. B. Newman, and I. J. Hirsh, "The difference between monaural and binaural thresholds," J. Exp. Psychol. 37, 229–242 (1947).

TABLE I. Thresholds* of pure tones masked by white noise (59.1 db S.P.L. per cycle).

Condition	Interaural phase relation: Tone (ϕ_T)	Interaural phase relation: Noise (ϕ_N)	Observer	Frequency of tone: 100	200	500	1000	2000	5000
1	Mon.	0	G	−34.8	−44.0	−41.8	−42.1	−37.4	−26.9
			H	−36.3	−39.2	−35.6	−27.8	−25.7	−22.3
			P	−33.2	−42.9	−38.6	−34.9	−31.8	−27.6
			Av.	−34.8	−42.3	−38.7	−34.9	−31.6	−25.6
			S.P.L.	73.2	65.7	69.3	72.1	74.4	80.4
2	Mon.	180	G	−31.2	−38.7	−40.7	−42.0	−37.0	−25.5
			H	−30.5	−33.9	−33.9	−27.5	−25.4	−22.8
			P	−31.0	−36.6	−36.8	−33.2	−31.4	−29.3
			Av.	−30.9	−36.4	−37.1	−34.2	−31.3	−25.9
			S.P.L.	77.1	71.6	70.9	72.8	74.7	80.1
3	0	0	G	−34.4	−37.8	−35.6	−41.2	−36.2	−25.8
			H	−32.8	−30.2	−29.8	−26.0	−24.0	−22.2
			P	−32.0	−34.0	−34.0	−31.2	−30.0	−26.0
			Av.	−33.1	−34.0	−33.1	−32.8	−30.1	−24.7
			S.P.L.	74.9	74.0	74.9	74.2	75.9	81.3
4	180	180	G	−31.6	−35.6	−36.0	−39.8	−34.8	−24.8
			H	−30.4	−27.8	−28.8	−27.4	−24.6	−21.0
			P	−31.8	−33.6	−33.0	−30.2	−30.8	−27.0
			Av.	−31.3	−32.3	−32.6	−32.5	−30.1	−24.3
			S.P.L.	76.7	75.7	75.4	74.5	75.9	81.7
5	0	180	G	−34.4	−44.4	−45.8	−46.2	−38.2	−28.0
			H	−33.8	−39.0	−39.0	−30.6	−27.6	−23.0
			P	−36.4	−41.4	−41.6	−37.0	−35.2	−32.0
			Av.	−34.9	−41.6	−42.1	−37.9	−33.7	−27.7
			S.P.L.	73.1	66.4	65.9	69.1	72.3	78.3
6	180	0	G	−37.2	−49.6	−46.8	−49.0	−39.0	−27.0
			H	−41.4	−44.4	−40.0	−32.0	−26.8	−23.4
			P	−37.2	−48.8	−44.8	−40.2	−32.0	−31.6
			Av.	−38.6	−47.6	−43.9	−40.4	−32.6	−27.3
			S.P.L.	69.4	60.4	64.1	66.6	73.4	78.7

* Thresholds in db re 0.1 volt across earphone (except S.P.L.).

which the different intensities were presented was different for each observer.

3. With a fixed intensity of noise in the two earphones and a constant frequency of the tone, thresholds were obtained for five different interaural phase relations of the tone combined with two interaural phase relations of the noise.

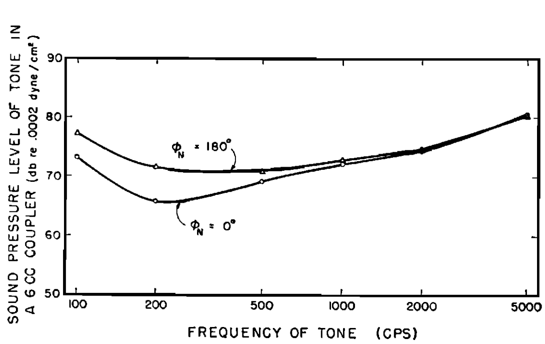

FIG. 2. Monaural thresholds of a pure tone masked by intense white noise (59.1 db S.P.L. per cycle). Each of the two curves represents a different interaural phase relation of the noise.

RESULTS

The binaural and the average monaural thresholds of six pure tones, masked by a 7000-cycle band of white noise whose sound pressure level per cycle (re 0.0002 dynes/cm^2) was 59.1 db, are presented in Table I. Each monaural threshold is the mean of ten judgments, five on each ear. Each binaural threshold is the mean of five judgments.

The data for the two monaural conditions (1 and 2) are presented graphically in Fig. 2. We note from these curves that the monaural thresholds, masked by binaural noise which is in phase, are lower than the monaural thresholds masked by binaural noise which is out of phase, especially between 200 and 500 c.p.s. The monaural thresholds which are graphed on the upper curve (for which the noise was out of phase at the ears) are consistently lower than the monaural thresholds in Hawkins' experiment[5] in which the same intensity of noise was presented only to the ear receiving the tone. The difference becomes smaller as the frequency of the tone increases. The threshold for a tone in one ear which is masked by noise in the same ear is higher than the threshold of the same tone masked by the same intensity of noise in both ears, whether the binaural noise is in or out of phase at the ears.[6]

The data for the four binaural conditions (3, 4, 5, and 6) are presented graphically in Fig. 3. The symbols ϕ_T and ϕ_N indicate the interaural phase relations of the tone and the noise, respectively. Here we note that the binaural threshold is lowest when the tone is out of phase in the two ears and the noise is in phase. The highest binaural threshold is observed when the tone and the noise are both out of phase. Summation and inhibition are shown graphically in Fig. 4,

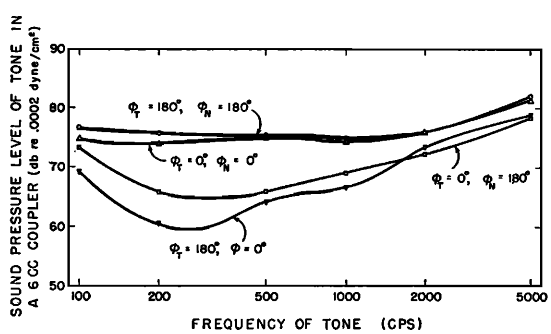

FIG. 3. Binaural thresholds of a pure tone masked by intense white noise (59.1 db S.P.L. per cycle). Each of the four curves represents a different combination of interaural phase relations of the tone and of the noise.

[5] J. E. Hawkins, *The Masking of Signals by Noise: Part I* (Psycho-Acoustic Laboratory, Harvard University, Cambridge, Massachusetts, October 1, 1945), OSRD 5387. (Available through the Office of Technical Services, U. S. Department of Commerce, Washington, D. C. PB L 68916.)

[6] In order to check the possibility that differences between the monaural thresholds presented here and those of Hawkins might be due to some factor other than the addition of the noise in the opposite ear, Dr. G. A. Miller and I have made some brief observations on the threshold of a 200-cycle tone presented against a background of (a) noise in the same ear or (b) noise in both ears. The monaural threshold does indeed decrease when the noise is added out of phase in the opposite ear. Not only that, but also a tone that is just above threshold in the presence of monaural noise seems to increase in loudness when the noise is added to the opposite ear.

TABLE II. Difference between average monaural and binaural thresholds of Table III (negative differences signify inhibition).

Conditions	Frequency					
	100	200	500	1000	2000	5000
1 and 3	−1.7	−8.3	−5.6	−2.1	−1.5	−0.9
2 and 4	0.4	−4.1	−4.5	−1.7	−1.2	−1.6
2 and 5	4.0	5.2	5.0	3.7	2.4	1.8
1 and 6	2.8	5.3	5.2	5.5	1.0	1.7

where the differences between the binaural and average monaural thresholds are plotted. Since Fig. 2 shows two monaural threshold curves for two interaural phase relations of the noise, the problem of expressing a monaural-binaural difference involves a selection from several possibilities. It was decided, arbitrarily, that the two binaural thresholds for which the noise was in phase should be compared with the monaural threshold for which the noise was in phase. Conversely, the two binaural thresholds with noise out of phase were compared with the monaural threshold for which the noise was out of phase. The average differences given in Table II are plotted in Fig. 4. A positive difference (monaural minus binaural) indicates that the binaural threshold is lower than the monaurel, i.e., binaural (or interaural) summation. A negative difference indicates that the binaural threshold is higher than the monaural, i.e., interaural inhibition. Figure 4 shows the frequency range over which interaural inhibition holds. We note not only that the inhibition for the homophasic conditions increases in this region of lower frequencies, but also that the summation for the

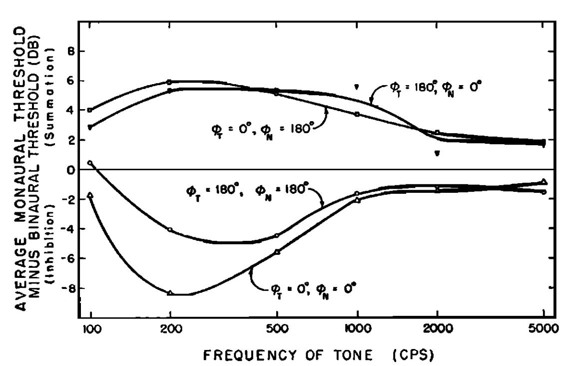

FIG. 4. Difference between the average monaural and binaural masked thresholds of a pure tone masked by intense white noise.

TABLE III. Thresholds* of a 200-cycle tone masked by white noise.

Condition	Interaural phase relation: Tone (ϕ_T)	Noise (ϕ_N)	Observer	Sound pressure level per cycle: −10.9	9.1	29.1	44.1	59.1
1	Mon.	0	G	−82.5	−77.5	−64.8	−54.4	−44.0
			H	−76.7	−74.7	−64.6	−51.8	−39.2
			P	−79.9	−76.8	−65.3	−54.2	−42.9
			Av.	−79.7	−76.3	−64.9	−53.5	−42.3
			S.P.L.	28.3	31.7	43.1	54.5	65.7
2	Mon.	180	G	−81.7	−76.8	−63.6	−51.5	−38.7
			H	−76.6	−72.6	−60.8	−47.9	−33.9
			P	−79.8	−75.7	−62.0	−48.8	−36.6
			Av.	−79.4	−75.0	−62.1	−49.4	−36.4
			S.P.L.	28.6	33.0	45.9	58.6	71.6
3	0	0	G	−86.4	−77.2	−63.0	−50.6	−37.8
			H	−79.0	−75.8	−60.6	−46.0	−30.2
			P	−80.2	−77.2	−61.8	−46.8	−34.0
			Av.	−81.9	−76.7	−61.8	−48.5	−34.0
			S.P.L.	26.1	31.3	46.2	59.5	74.0
4	180	180	G	−86.0	−80.0	−65.0	−50.2	−35.6
			H	−78.2	−75.2	−58.8	−43.8	−27.8
			P	−85.2	−78.0	−62.2	−46.8	−33.6
			Av.	−83.1	−78.4	−62.0	−46.9	−32.3
			S.P.L.	24.9	29.6	46.0	61.1	75.7
5	0	180	G	−85.8	−81.2	−68.2	−56.6	−44.4
			H	−79.4	−76.6	−64.4	−52.4	−39.0
			P	−82.2	−78.8	−67.0	−54.6	−41.4
			Av.	−82.5	−78.9	−66.5	−55.2	−41.6
			S.P.L.	25.5	29.1	41.5	52.8	66.4
6	180	0	G	−87.6	−81.4	−70.0	−59.8	−49.6
			H	−81.0	−78.8	−68.4	−57.6	−44.4
			P	−82.4	−82.2	−69.8	−59.0	−48.8
			Av.	−83.7	−80.8	−69.4	−58.8	−47.6
			S.P.L.	24.3	27.2	38.6	49.2	60.4

* Thresholds in db re 0.1 volt across earphone (except S.P.L.).

antiphasic conditions increases in approximately the same region.

The data of Figs. 2, 3, and 4 indicate that a frequency of 200 c.p.s. would be a likely candidate for the investigation of summation and inhibition, under the six interaural phase conditions, as a function of the intensity of the white masking noise. Six intensities of noise were used corresponding to sound pressure levels per cycle (re 0.0002 dynes/cm^2) of −10.9, 9.1, 29.1, 44.1, and 59.1 db. The thresholds and the binaural-monaural differences are given in Tables III and IV.

The average monaural thresholds for the two interaural phase relations of the noise are plotted in Fig. 5. Here we note again that the monaural threshold is lower when the noise is in phase than when the noise is out of phase. The difference becomes larger as the intensity of the noise increases.

The binaural thresholds for the two homophasic and the two antiphasic conditions are plotted in Fig. 6. The differences among the four conditions become greater as the intensity of the noise increases to the highest intensity of noise used. The data for this intensity of noise correspond to the data for 200 c.p.s. in Fig. 3.

According to the criteria for comparison discussed above in connection with Fig. 4, the differences between the average monaural and binaural thresholds for the 200-cycle tone are plotted as a function of the intensity of the masking noise in Fig. 7. The curve of differences for which both the tone and the noise are in phase corresponds well with the comparable curve for 250 c.p.s. in the previous report.[1]

TABLE IV. Differences between average monaural and binaural thresholds of Table V (negative differences signify inhibition).

	S.P.L. per cycle of noise				
Conditions	−10.9	9.1	29.1	44.1	59.1
1 and 3	2.2	0.4	−3.1	−5.0	−8.3
2 and 4	3 7	3.4	−0.1	−2.5	−4.1
2 and 5	3.1	3.9	4.4	5.8	5.2
1 and 6	4.0	4.5	4.5	5.3	5.3

Since the phenomena of inhibition and summation are clear for a frequency of 200 c.p.s. and an intensity of noise of 59.1 db (S.P.L. per cycle), these two parameters were held constant, in the third sub-experiment, while the interaural phase relation of the tone was varied from 0° to 180° in steps of 30°. The seven phase relations were used both when the noise was in phase and when the noise was out of phase. The average monaural and binaural thresholds are presented in Table V.

The differences between the average monaural and binaural thresholds, as a function of the interaural phase relation of the tone, are presented graphically in Fig. 8. Each of the two curves represents one of two interaural phase relations of the noise.

The end points at 0° and 180° indicate what has already been shown, *viz.*, that interaural summation holds when the tone and noise have opposite interaural phase relations and that interaural inhibition holds when the interaural phase relations of the tone and noise are the same. The data for 90° are interesting for two reasons: first, the two curves cross at about 90°, and second, the crossing takes place at a summation of approximately 3 db. Both curves rise rapidly from inhibition to a summation of about 3 db, and then decelerate toward higher values of summation.

DISCUSSION

A discussion of the results presented in Figs. 2–8 should begin with one further observation. It has to do with the apparent location in the head of the different sound stimuli. Observations reported by Langmuir *et al.*[7] and Licklider[2] indicate that a noise which stimulates both ears in phase seems to be located in the center of the head. It has a hard and compact quality. On the other hand, when the noise stimulating the two ears is out of phase, it seems to be located at the ears. The introspections of all three subjects in this experiment support these observations. Pure tones may also be localized in the middle of the head when the interaural phase is 0° and out at the ears when the interaural phase is 180°. This judgment seems to be relatively easy for frequencies near 200 c.p.s. Indeed, we note from the data of Langmuir *et al.*[7] that the

TABLE V.

	Observer	Monaural (av.)	Binaural Interaural phase relation of tone (ϕ_T) 0°	30°	60°	90°	120°	150°	180°
Noise: in phase ($\phi_N=0°$)	G	−39.2	−34.6	−37.8	−41.4	−43.0	−46.8	−43.8	−46.8
	H	−39.2	−31.4	−36.2	−40.8	−42.4	−44.6	−44.4	−45.8
	P	−45.3	−36.8	−41.0	−42.8	−48.0	−48.8	−48.2	−51.4
	Av.	−41.2	−34.3	−38.3	−41.7	−44.5	−46.7	−45.5	−48.0
	S.P.L.	66.8	73.7	69.7	66.3	63.5	61.3	62.5	60.0
Difference between average monaural and binaural thresholds			−6.9	−2.9	0.5	3.3	5.5	4.3	6.8
Noise: out of phase ($\phi_N=180°$)	G	−40.4	−45.8	−45.6	−45.8	−42.0	−42.4	−36.8	−32.2
	H	−35.2	−40.4	−40.4	−38.0	−37.6	−34.2	−32.8	−30.6
	P	−38.3	−42.8	−42.4	−41.0	−41.2	−41.0	−37.8	−36.0
	Av.	−38.0	−43.0	−42.8	−41.6	−40.3	−39.2	−35.8	−32.9
	S.P.L.	70.0	65.0	56.2	66.4	67.7	68.9	72.2	75.1
Difference between average monaural and binaural thresholds			5.0	4.8	3.6	2.3	1.2	−2.2	−5.1

[7] I. Langmuir, V. J. Schaefer, C. V. Ferguson, and E. F. Henelly, *A Study of the Binaural Perception of the Direction of a Sound Source* (General Electric Company, Schenectady, New York, 1944) OSRD 4079. (Available through the Office of Technical Services, U. S. Department of Commerce, Washington, D. C., PB 31014).

error in this judgment increases as the frequency increases from 200 to 1200 c.p.s. Above 1200 c.p.s. this judgment of localization cannot be made.

It is tempting to redescribe the quantitative data of the present experiment in terms of the location of the tone and the noise in phenomenal space. First, let us consider the data that indicate that the monaural threshold is lower when a tone is masked by binaural noise which is in phase than when it is masked by binaural noise which is out of phase. The monaural threshold is lower, in other words, when the tone is localized at one ear and the noise is in the middle of the head than when the tone is at one ear and the noise is at both ears.

In the case of binaural thresholds, the description is equally simple. The binaural threshold is much lower for antiphasic conditions than it is for the homophasic conditions. This is to say that a tone may be heard more easily when it sits in the middle of the head while the noise sits out at the ears or vice versa than when both the tone and noise are localized in the same place. This difference in the binaural thresholds for antiphasic and homophasic conditions decreases as the frequency increases from 200 c.p.s. Otherwise said, the difference between binaural thresholds for antiphasic and homophasic conditions becomes smaller as the tone becomes less localizable on the basis of phase.

This description in terms of the apparent positions of the tone and noise in space would take on the character of a description at the physiological level if we could assume an isomorphic relation between events in phenomenal space and their correlated patterns of activity in the cortex. Let us naively suppose, for example, that the perception of a tone of low frequency depends upon there being a certain surplus of neural activity, in a certain region corresponding to the tone, over and above the neural activity that would be present in the same region due to spontaneous activity or to random noise. Let us further suppose that the phase relation between the two ears determines, at least in part, the locus of distribution of such neural activity in the auditory cortex. Now if the distributions of activity from the tone and from the noise happen to coincide spatially in the cortex—as they would under homophasic conditions—the amount of neural activity corresponding to the tone would have to be relatively great in order that there be the surplus necessary for the perception of the tone. On the other hand, if the distributions of neural activity corresponding to the tone and to the noise were remote from each other in space—as they would be under antiphasic conditions—the level of neural activity corresponding to the tone could be relatively small and still produce the necessary surplus.

Although such speculation may not lead directly to testable hypotheses, it provides a convenient frame of reference for thinking about the

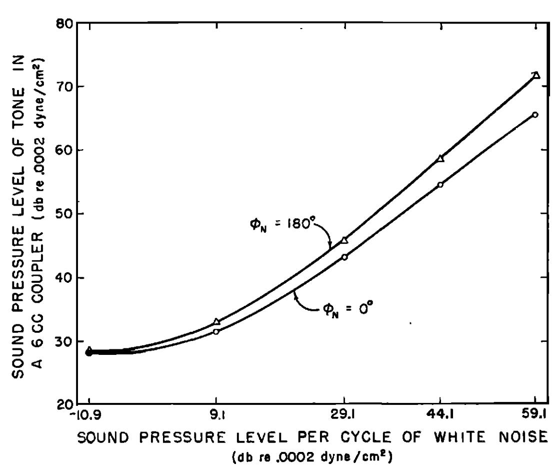

FIG. 5. Monaural thresholds of a 200-cycle tone masked by white noise. Each of the two curves represents a different interaural phase relation of the noise.

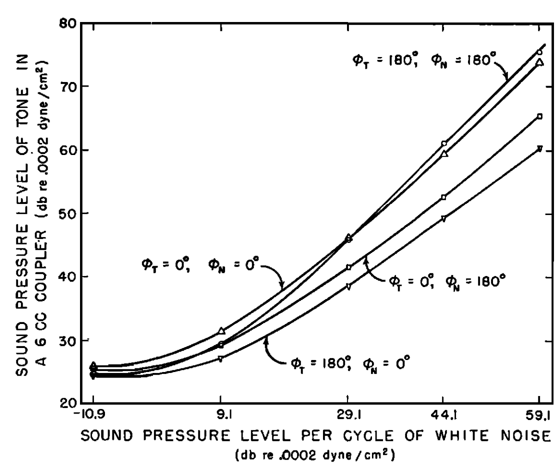

FIG. 6. Binaural thresholds of a 200-cycle tone masked by white noise.

many problems that are posed by the data. Other than this heuristic function, physiological theorizing offers little in the way of explanation of the phenomena which have been observed.

At a less speculative level, the present data tend to limit the generality of certain concepts in contemporary auditory theory. First, there is the concept of critical band width and its appli-

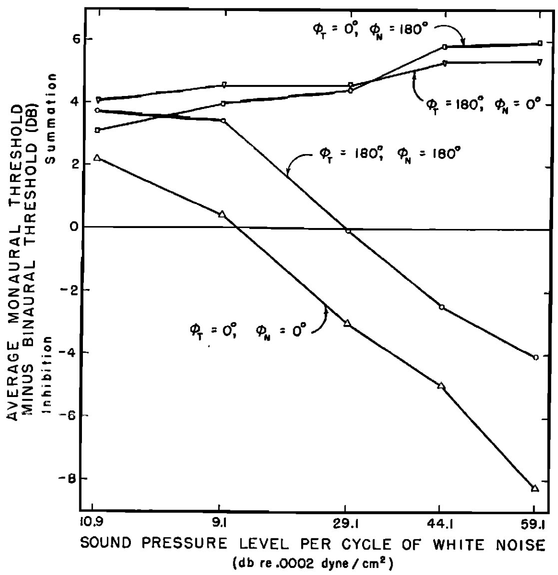

FIG. 7. Difference between average monaural and binaural thresholds of a 200-cycle tone masked by white noise.

cation to binaural hearing. French and Steinberg[8] present two graphs relating critical band width to frequency, one for monaural and one for binaural hearing. The critical band width is the width, in cycles or decibels (10 log cycles), of a flat band of noise which just masks a tone whose intensity is equal to the over-all intensity of the band and whose frequency lies approximately at the center of the band. French and Steinberg report that, for frequencies below 3000 c.p.s., the critical band width for binaural hearing is about 2 db below that for monaural hearing. The data of the present experiment indicate that the binaural critical band width must depend upon interaural phase relations. Not only that, but the critical band width for certain interaural phase relations must vary as a function of the intensity

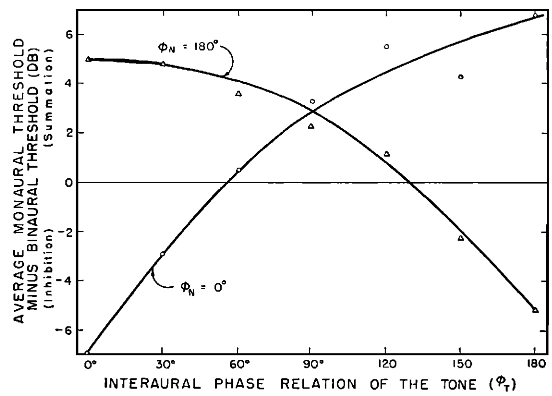

FIG. 8. Difference between average monaural and binaural thresholds of a 200-cycle tone masked by intense white noise (59.1 db S.P.L. per cycle).

of the noise, a dimension with which the critical band width was thought to be invariant.

Another notion which may need revision in the light of the results of the present experiment is that masking is entirely a peripheral phenomenon. A typical statement of the nature of masking is given by Steinberg and Gardner:[9] "The fact that the threshold of the tone is raised due to the presence of the masking sound, may be taken to indicate that some of the nerve fibers in the region on the basilar membrane that responds to the tone are busy sending impulses due to the masking sound." In their chapter on masking and fatigue, Stevens and Davis[10] suggest that there are two possible kinds of masking, central and peripheral, but state further that "central masking is relatively small." Their succeeding theoretical discussion of masking, however, is in terms of patterns of excitation on the basilar membrane or in the auditory nerve. In 1944, Galambos[11] suggested: "If it be conceded that these figures (concerning inhibition of single auditory fibers) illustrate processes underlying masking, then masking occurs not because fibers are kept busy discharging, but because they are prevented from doing so." Although Galambos does not state that the inhibitory phenomena of single fibers actually underlie masking, he offers

[8] N. R. French and J. C. Steinberg, "Factors governing the intelligibility of speech sounds," J. Acous. Soc. Am. **19**, 90–119 (1947).

[9] J. C. Steinberg and M. B. Gardner, "The dependence of hearing impairment on sound intensity," J. Acous. Soc. Am. **9**, 11–23 (1937), p. 15.

[10] S. S. Stevens and H. Davis, *Hearing* (John Wiley and Sons, Inc., New York, 1938), p. 214.

[11] R. Galambos, "Inhibition of activity in single auditory nerve fibers by acoustic stimulation," J. Neurophysiol. **7**, 287–304 (1944), p. 302.

the concept as a possible alternative to that of Steinberg and Gardner.

These views have in common an implicit assumption that the mechanism of masking is determined at the periphery, either in the cochlea or in the auditory nerve. Much of what we call masking may be thus determined, but we can be fairly sure that peripheral masking is not the whole story. If masking were entirely a peripheral phenomenon, there should be no shift in the monaural threshold of a 200-cycle tone that is masked by noise in one ear when noise is added to the other ear, nor should there be further shifts when the interaural phase relation of the noise is changed. We have observed, however, that there are such shifts. It seems obvious that some central interaction must take place.

Finally, we shall examine the notion that the binaural system is a simple summating device. We may begin by considering the simplest case in which the two monaural systems act like independent feeders, supplying nerve impulses to some central point of convergence. This simple notion was discarded as much as a hundred years ago by Seebeck[12] who observed that the tone of a siren sounded louder to two ears than to one, whether the tones were in or out of phase. The concept of a system of two independent feeders must then be so modified that physical summation may obtain no matter what the phase relation of the patterns of energy which come from the two sides. Presumably, this is the kind of system that was conceptualized by Hughes[13] and by Caussé and Chavasse.[14] In the case of pure tones masked by noise, such a system would predict that, since both the tone and the noise from the two ears "add up," there could be no difference between the monaural and binaural thresholds, because the signal-to-noise ratios would be the same monaurally and binaurally. It has been shown here, however, that under certain conditions the binaural threshold is lower than the monaural and, strangely enough, that under certain other conditions the binaural threshold is higher than the monaurel. For the present, at least, it seems that the hypothesis which relegates the differences between binaural and monaural thresholds to a simple arithmetic summating device might well be modified to explain the data on masked thresholds.

To summarize, the masked thresholds for low frequency tones are related to the phase relation between the two ears of the tones and of the noises. When a tone, presented to one ear, is masked by a noise in both ears, its threshold is lower when the noise is in phase than when the noise is out of phase. Binaural thresholds are higher than monaural thresholds when both the tone and the noise have the same interaural phase relations. Binaural thresholds are lower than the corresponding monaural thresholds when the tone and the noise have opposite interaural phase relations. These effects are most prominent in the vicinity of 200 c.p.s. and they become greater as the intensity of the masking noise is increased. For fixed interaural phase relations of binaural noise, interaural summation and inhibition are continuously variable with the interaural phase relation of the tone. These observations indicate that the present hypotheses concerning masking and binaural summation need to be expanded to include central factors.

[12] A. Seebeck, "Beiträge zur Psychologie des Gehör- und Gesichtsinnes, Abschn. A., Pogg. Ann. **68**, 449–458 (1846).

[13] J. W. Hughes, "The monaural threshold: Effect of a subliminal contralateral stimulus," Proc. Roy. Soc. **124B**, 406–420 (1938).

[14] R. Caussé and P. Chavasse, "Recherches sur le seuil de l'audition binauriculaire comparé au seuil monauriculaire," Comptes rendus Soc. Biol. Paris **85**, 1272 (1941).