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In a preliminary study of the phenomena of localization by the method of temporal difference of arrival of sound at the two ears, we find results which so nearly coincide with results obtained by Stewart (1) and by Halverson (3) who studied the problem by means of continuous sounds of varying phase relations at the ears, that we feel justified in presenting here the phase-theory as a time-theory in sound localization.

The phase-theory, now a quarter-century old, (4) (5) (6) (7) (8) (9) holds that the localization of the phantom source is on the side of the ear receiving the leading phase when two tones of the same frequency and of equal intensity are brought to the ears. If like phases arrive at the respective ears simultaneously, localization is in the median plane. When the phase leads to either side, the phantom source shifts to that side and describes an arc of 90 degrees from the median plane to the aural axis, as the leading phase increases in lead to exactly one-half wave-length, at which time the two tones are again in phase. Further increase in lead after this point changes the localization to the other side, and the course is described in the reverse order, the phantom coming again to the median plane, when the leading tone is just exactly one wave-length ahead of the other.

The time-theory, the most recent theory to account for "rightness" and "leftness" in the localization of sound, is accredited to von Hornbostel and Wertheimer (10) and Klemm (11). These investigators have developed techniques for the study of the phenomena of localization, which employ single sharp sounds instead of continuous sounds at the ears. Briefly stated the theory is as follows: If two sharp sounds of like quality and of equal intensity are exposed simultaneously to the two ears, localization is in the median plane. If they are exposed so that one is prior to the other by a very small temporal difference, localization is on the side of the prior sound. As the temporal difference increases in magnitude the sound swings through an arc of 90 degrees from the median plane to the axis of the ears. Banister (2) has extended the theory somewhat, but the above statement is adequate for the treatment of the subject here.

From these definitions of the theories under consideration, it is easy to arrive at the proposition treated specifically in this paper. Differences in phase of two tones of the same frequency and of equal intensity presented at the ears are but differences in time of arrival of like phases at the ears. If, by any means, like phases could be detached from the continuous sounds and presented alone, the situation would be the same as when two discrete diotic sounds of like quality and of equal intensity are exposed to the ears so that one is prior to the other by very small temporal differences, the range of the temporal differences being that represented by a half wave-length of the continuous sounds. A knowledge of the function of temporal differences in sound localization therefore makes possible the prediction of localization according to varying phase relations of various frequencies.

In support of this proposition data are presented which have been compiled from the preliminary stages of a very thorough study, now being carried forward, of the problem of sound localization. A "single impulse" technique is being employed. The discrete sounds are set up by electric sparks which are generated by breaking currents of 5.5 amperes at 6 volts, through separate induction coils of identical type. The spark gaps at both sides are equal (.5 mm.). This gives fair assurance that the sounds at the ears are qualitatively alike and of equal physical intensity. The observers are seated, singly, in a sound-prcof room, midway between the two sound sources, 72 cm. from either spark gap, while the experimenter, in a distant room, controls by means of a pendulum device the time of arrival of the sounds. As a signal to the observers, the experimenter disconnects the light in the sound-proof room. The light is turned on again for the *O*'s to record their estimates of the angular distance of the sound from the median plane to the right, or to the left.

The data given here will doubtless undergo refinement as the investigation progresses, but they indicate in a general way the function of the temporal difference of arrival of sound at the ears, in auditory localization. Table I presents a summary of 380 localizations made by various *O*s of the sound in the mid-region.

Table I shows that localization remains medial until the temporal difference between the two sounds has become as great as .1 sigma. Klemm's (11) figure representing this difference is 2 sigma sigma, while von Hornbostel and Wertheimer (10) conclude that

TABLE I. DISTRIBUTION OF 380 JUDGMENTS OF LOCALIZATION IN THE MID-REGION, ON A SCALE OF TEMPORAL DIFFERENCES RANGING FROM 0 to .16 SIGMA (BY PERCENTAGES)

Temporal Differences		Localization	
Sigma	Median	Right-left (Expected)*	Right-left (Unexpected)*
0	58	—	42
.0012	39	33	28
.0025	44	44	12
.005	32	39	29
.01	36	23	41
.02	20	41	39
.03	32	60	8
.04	28	48	24
.06	22	56	22
.08	49	39	12
.10	7	86	7
.12	30	70	0
.16	11	84	5

(* By "expected" is meant that the fused sound was localized as right, or left, when the sound on the right, or left, was prior. "Unexpected" means that localization was on the side opposite to the prior sound.)

the magnitude of the difference at this point is 30 sigma sigma. But we observe form Table II, below, that when the temporal difference is .12 sigma, the fused sound is localized as being only 5 degrees from the median plane.

It is evident from Table II that as the temporal difference is increased, the angular displacement of the sound is also proportionally increased. The relation between the temporal differences and the angular displacement is approximately linear, as seen from

TABLE II. HOW TWO OBSERVERS LOCALIZED AS THE TEMPORAL DIFFERENCES INCREASED FROM 0 to 1.56 SIGMA

Temporal Differences in Sigma	Observer H	Observer S	Average H — S
0	x [1]	x	x
.12	5 [2]	5	5
.24	13	9	11
.36	22	14	18
.48	42	20	31
.60	57	33	45
.72	66	32	49
.84	74	50	62
.96	80	61	71
1.08	87	72	80
1.20	83	82	83
1.32	89	86	88
1.44	86	85	86
1.56	89	90	90

1 "x" represents an unknown here because of an occasional error in localization, either to the right or to the left.

2 Each of these numbers is the average of eight estimates of the angular displacement of the fused sound from the median plane. This does not apply to the last column.

Fig. 1. The course of the phantom sound, according to the reports of all *Os*, is more or less a curved line. The sound is described as swinging out from the median plane, keeping at a more or less constant distance (varying from 5 cm. to 60 cm. with different *Os*) from the head until it is somewhere in the region of 80 degrees from the median plane when it moves very rapidly in to the ear. The sound comes to the maximal lateral position when the temporal difference is about 1.08 sigma. Von Hornbostel and Wertheimer hold the time difference here to be only 630 sigma sigma. But we note in Fig. 1 that the straight line relation holds uniformly up to the 1.08 sigma ordinate.

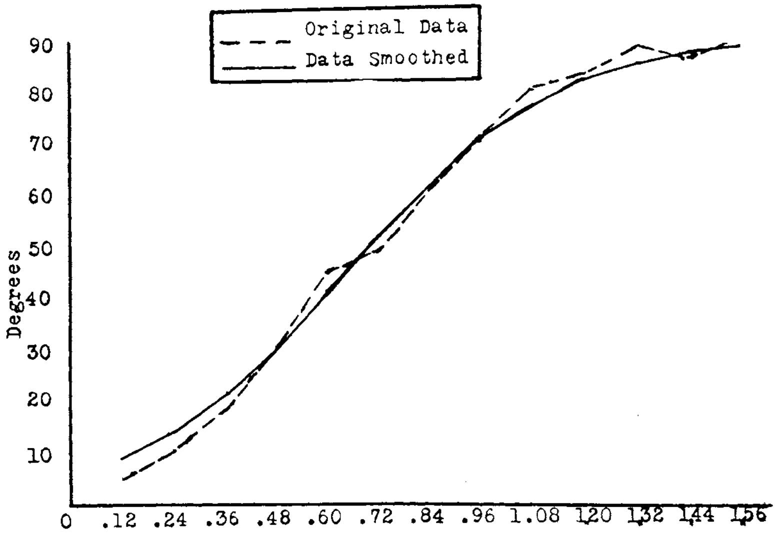

Fig. 1. Curves of Data Presented in Table II.

Stewart (2) in discussing his quantitative measurements of the binaural difference of phase effect says (page 38), "The experiments showed clearly that the angular displacement of the apparent source of the fused sound or 'image' is strictly proportional to the phase difference at the ears, with, of course, the limiting provision that the linear relation is true only for a difference of phase, Φ, less then 180°." Again (page 41), in the same report, he states that, "It must be pointed out that if such a straight line as in Fig. 3, when extended, passed through the origin, it would indicate that Φ, the angular displacement, is strictly proportional to the difference in the time of arrival at the ears of a given phase, and that this is independent of frequency." Table I shows that localization will remain median even when the leading phase is about .1 sigma ahead of the other. Figure 1 indicates that this condition of lag and lead does not hold throughout. This would account for the fact that Stewart's straight line did not pass through the origin, since time does not mean displacement until after a difference of .1 sigma, after which displacement is strictly proportional to the time difference of arrival of like phases at the ears. Bowlker (13), in 1908, published experimental results in which he concluded that tones of low pitch were localized by the difference of time of arrival of corresponding parts of the same wave at the two ears. Halverson's (2) diagram and description of the path of the phantom (page 12) is representative of the descriptions which the *O*s used in this study give of the course of the fused sound as temporal differences are increased from 0 to 1.32 sigma. It would seem safe to conclude from this that a phase-difference is but a temporal difference.

Proceeding on the conclusion that phase is time, it is possible (14) to indicate from the results of this preliminary investigation the behavior of localization according to varying phase relations of various frequencies. Tones presented to the two ears may be as much as .1 sigma different in phase and the localization of the apparent source be in the median plane. When the phase difference can not be more than .1 sigma (*i.e.*, frequencies above approximately 5000 d.v.) the localization is always median if phase difference is the determining factor. Tones of frequencies below about 460 d.v. (*i.e.*, whose phase difference is 1.08 sigma, or less) down to a point where double maximal lateral localization begins, have normal, complete localization, *i.e.*, complete swing through the 90 degrees arc from the median plane to the aural axis as one phase leads the other. When the frequency of the tone is above 460 d.v., localization never comes exactly to the 90 degrees position; and the path of the phantom is very gradually restricted as the frequencies increase from this point, localization becoming less and less distant from the median plane until 5000 d.v. is reached, when localization becomes medial, and remains so with further increase of frequency.

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