The role of wave-phase in the intensity theory of the localization of sound

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THE ROLE OF WAVE-PHASE IN THE INTENSITY THEORY
OF THE LOCALIZATION OF SOUND

by

FREDERICK CARL BRUENE

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of the State University of Iowa in partial
fulfillment of the requirements for the Degree
of
Master of Arts

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PREFACE

The writer here desires to express his thanks and appreciations to Dean Seashore, who suggested this problem for investigation and who has given valuable counsel and advice throughout this series of experiments. He is also very thankful to Dr. Williams for the helpful assistance given in making the present investigations. The writer also wishes to express his thanks and gratitude to Professor Stewart with whose apparatus and under whose supervision and direction the first series of experiments were conducted. He is also very much indebted to him for permitting the data obtained in these experiments to be used in the present work. He furthermore desires to acknowledge his obligation to his fellow-students who assisted in making the observations.
INTRODUCTION

This problem has grown out of investigations made into the nature and method of sound localization; in fact, it presents one phase of this field. It was discovered that the localization of a sound changed when the difference in phase between the separate waves striking the ears changed. It was further observed that the position of the sound had a definite relation to the degree of phase-difference. The purpose in the present experiments is to extend, if possible, the knowledge of the nature and cause of this phenomenon, also to determine what part, if any, it plays in everyday sound localization.
The first study of the influence of phase difference in the localization of a sound produced by leading two sounds of differing phase to each ear separately, was probably that carried on by Professor S. P. Thompson (Phil. Mag. Vol. 6, p. 383, 1878). He used three methods; first, by using two India rubber tubes of equal length as sound conductors, one for each ear. The sound was produced by two tuning forks, one at the open end of each tube. The phase difference was produced by turning one of the forks round on its axis or by weighting it and so obtain a continually changing phase. Second, by using only one tuning fork but having branching tubes to the ears and making the branches differ by one-half the wave length. Third, by a system of telephones in which the receiving telephones were in reversed action. In addition to this he used a strong copper wire, three feet long, putting one end in each ear, and sliding the stem of a tuning fork back and forth upon the wire and so changing the phase. He came to the following conclusions:

1. "When two simple tones in unison reach the ears in opposite phases, the sensation is localized at the back of the head."
2. "The localization of this acoustic 'image' is independent of the pitch of sounds."

3. "When the difference of phase is partial, the sensation is localized partly in the ears and partly at the back of the head."

4. "If the difference of phase be complete but the intensities unequal, the acoustic 'image', instead of being at the middle of the back of the head, is nearer that ear in which the sound is louder."

5. "It is possible to discern the difference between two compound tones which differ only in phase but not in the pitch or intensity of their component partial tones."

6. "Vibrations mechanically conveyed to a point of the parietal or occipital region of the skull at one side (by means of holding a tuning fork on the head) are apparently heard in the ear at the other side of the head." He does not speak of a distinct lateral localization, but emphasizes the localization in the back of the head when phases are opposite."

Rayleigh. An account of the work of Lord Rayleigh is given in his article "On our Perception of Sound Direction" (Phil. Mag. Vol. 13, p. 214 ff., 1907). Lord Rayleigh was led to carry on experiments upon the influence of phase difference in sound localization by the fact that with tones below 256 vd. the difference of intensity at the two ears becomes so very small that, he thinks, it can hardly be a factor in the localization of sound. He shows that at 128 vd. the difference of intensity would be decidedly less than 1 per cent of the whole. Experiments showed, however, that tones of low pitch can be localized with as much accuracy
as higher tones. The other alternative is that the phase difference at the ears enters into the determination of the location of low tones. Rayleigh then devised several experiments by means of which he brought conditions, to a certain degree at least, under experimental control. By means of tuning forks and resonators he found that a fork of 128 vd. can be localized without difficulty. He then took a fork of 96 vd., where the difference of intensity between the two ears is not more than 2 parts per thousand. Here, also, he found no difficulty in localizing the sound at the sides. His next attempt was to find out whether a fork having a retardation of 1/2 period at the ear farthest from the source when the source of sound is toward the side, in which case phase difference would not aid localization, is localized with greater difficulty than the lower tones. There was, however, no difficulty. He then came to the conclusion that for a tone of 512 vd. the intensity difference is great enough to determine the location of the sound, but that with low tones phase differences are the determining factors.

Rayleigh then proceeded to confirm the statement that we cannot only appreciate phase differences, but that this
appreciation is fundamental to judgments as to direction of sound, especially to localization at the sides. He used two electrically maintained tuning forks, each in a separate room, as sources; the sound from one fork was conducted by means of pipes to one ear, the sound from the other fork to the opposite ear. The sounds were made as weak as possible. The forks were so tuned that a period of from 5 to 10 seconds could be obtained at will. Precautions were taken to prevent any interference outside of the head. Rayleigh says that "we at once experienced a right and left effect, the sound appearing to transfer itself alternately from the one side to the other. When the effect was at its best, the sound seemed to be entirely on one side or on the other." He also observed that the intensity at the two ears needs to be only approximately equal; that the right and left effects are perceived through a considerable range of variation of intensity; but that the best effects are obtained when the intensities at the two ears are equal. "The sound seemed to be predominantly on the right or on the left for almost the whole of the cycle, the transitions occupying only small fractions of the whole time." When the vibration on the right side was the quicker, the right localization followed the agreement of phase, and the sensation of left followed the opposition of phase. The
opposition of phase, represented by silence, was extremely well marked. This part of the cycle seems for Rayleigh to have been more distinct than the agreement or maximum. He also says that phase agreement and opposition are not definitely connected with front and back sensations; the direction of the revolution seemingly may vary. This is somewhat in disagreement with Professor Thompson's conclusions.

Through several other somewhat different experiments which Lord Rayleigh performed he further confirmed the results already obtained. In experimenting with forks of higher pitch he observed that beyond 320 vd. the lateral effects were more difficult to obtain than with the lower tones. With these results as evidence, Lord Rayleigh regards it as established that up to pitch g' phases differences are attended with marked lateral effects.

More and Fry. In 1907 Professors L. T. More and H. S. Fry published an article "On the Appreciation of Phase-difference and Its Importance in Sound Localization" (Phil. Mag. Vol. 13, p. 452, 1907). Thus these experiments were carried on independently of the work done by Lord Rayleigh. More and Fry give three reasons to
support the theory of phase perception. First, experiments made on animals, as the horse, whose ears are located close together on the top of the head. In this case the head can make no shadow, and consequently cannot interfere with the intensity at the two ears. The results of such experiments apparently show that such animals locate sounds accurately. Second, the fact that complex tones, as that of the human voice, can be located in the median plane. In this case neither difference in intensity nor in phase exists, but it is supposed that the outer ear modifies the short waves of the higher tones and so brings about a difference. Third, the results obtained from their own experiments. These consisted in placing an observer in the center of a circle which was divided by radii every 22 1/2°. 0° was directly behind the observer, 180° was in front, −90° to the right, and 90° to the left of the observer. By means of two rubber tubes the sound was conducted from a Y tube to the ears, one end of each tube ending in one of the ears, the other two ends being attached to the Y tube. At the open end of the Y tube the source of the sound was placed. This consisted of either a tuning fork or the human voice. The phase at the ears was varied by inserting glass tubes into one or the other of the tubes leading to the ears.
The results of these experiments show that a variation in the length of the tube by two centimeters shifted the location of the sound. He finds that "up to a certain increase in phase-difference, the change of direction increases regularly and uniformly. But when the phase-difference becomes greater than $3/8$ wave-length, for wave-length $= 64$ cm., and $1/4$ wave-length, for wave-length $= 104$ cm., decision is more difficult, the apparent direction remaining unchanged to some and to others the angle is diminished." They observed no change in the intensity of the sound for the different phase relations; not even when the phases were directly opposite was there a decrease in intensity. The effect was as if the fork had been sounded in the free air at different points on the circumference of the circle. The evidence given by these results and the two above mentioned reasons are the evidence given by More and Fry in support of the theory that phase differences are essential in localizing sounds.

Wilson and Meyer. In 1908 Wilson and Meyer published an article on "The Influence of Binaural Phase Differences on the Localization of Sound" (British Journal of Psychology, Vol. 2, p. 363, 1908). In this article they describe a new method of experimenting, give the results of a series of experiments, and offer an explanation of the results obtained.
Their apparatus consisted of two permanent tubes, used as conductors. The phase at the ears was changed by a T piece which consisted of a pipe of such size that it would slide into the other tubes. The source used was a tuning fork. This apparatus is similar to one used in the present experiments, which will be described more in detail later.

The results of their experiments may be summed up as follows: A slight movement of the T piece from the middle point would shift the sound toward the shorter tube. When the T piece was moved still farther in the same direction, the sound traveled to a distinct lateral position on the side of the shorter tube, then it gradually came back to the median plane; from there it traveled to the side of the longer tube; and after having reached a distinct lateral position on this side, returned gradually to the median plane. The sound was located on the side of the shorter tube when the opening in the T piece was between the middle point and 1/4 wave-length, or between 1/2 and 3/4 wave-length; on the side of the longer tube when the opening was between 1/4 and 1/2 wave-length, or 3/4 and 1 wave-length from the middle point.
No changes in the lateral effects were found by using forks of different frequency — 384, 128, 180, 240, 256, 320, and 512; neither were there changes when high tones emitted by König's steel rods were used as the source. "As a rule the localization of the tone presented little difficulty."

With forks 128 and 256, when the observer was facing the source, the sound seemed to come sagitally through the forehead when judged middle; when it was judged distinctly at the side it appeared to come coronally across the head. Intermediate positions appeared to come from positions between these two directions. The 348 fork did not give such well marked right and left effects. With the 512 fork "all the lateral effects came strongly or weakly across the head from ear to ear, none came from an oblique position."

When two forks of different pitch were presented at the same time, each acted in about the same way as when presented alone.

"As a rule, judgment of direction was not influenced by the loudness of the tone."

Occasionally when the tone was localized in one ear, there was a 'buzz' in the other ear. This 'buzz' probably affects localization to a certain degree.
In a number of consecutive judgments, the 'inertia of judgment' -- the tendency to give the same answer -- was found to be present.

The perception of phase-differences or lateral effect is present even though the intensity at the two ears is somewhat greater in one ear than in the other. The ears become adapted to the intensities, and this adaptation tends to persist even though the intensities are changed.

It was also found that resonance in one or both of the tubes may greatly disturb the correct localization.

From these results Wilson and Meyer conclude that binaural differences are "primary causes" of the lateral effects. They do not, however, assume that these effects are due to a direct perception of the phase, but they "are ultimately referable to binaural differences of intensity." They make three assumptions in their explanation: first, "that the sound entering one ear is transmitted through the bones of the head to the internal ear of the opposite side; second, that the retardation in phase, due to this ear to ear conduction is small; and, third, that the two (direct and transmitted) sets of waves, at their meeting in one or the other ear, arrive from opposite directions."

Their explanation is that the sound coming through the head, by means of bone conduction, in which conduction
there is a retardation in phase, will so reinforce the sound coming directly to the ear that at $90^\circ$ or $270^\circ$ the intensity at one or the other side will be strongest, while at $0^\circ$ and $180^\circ$ the intensity in the two ears will be equal. This possible shifting of intensity from one ear to the other will, according to Wilson and Meyer's demonstration, explain the different localizations which take place.

Rostosky. His work, entitled "Über Binaurale Schwebungen", was published in 1902. (Phil. Studien, Vol. 19, p. 557, 1902). In this article he describes, besides an investigation of binaural beats, several experiments made by himself on the change in localization produced by changes in phase-relations. This article, so far as the other work done in this field is concerned, seems to have been lost, since it is not referred to in any of the more recent publications. In fact, the article was not found until the present experiments had been practically completed, so that our work was carried on entirely without knowledge of his methods and results.

In one of his experiments he used two metal tubes, one leading to each ear. The tubes were not in direct contact with the ears, but were kept at a short distance from them. The same source was used for each tube; the phase differences were regulated by means of lengthening
the tubes, corrections for changes in intensity were made at the ears. In this case the sound moved from the median plane toward the side of the shorter tube; it remained on this side until a difference of nearly half a wave-length in the lengths of the tubes had been made; then it usually moved rapidly around the back of the head and appeared before the ear to which the long tube was leading; it again returned to the median plane when the difference was equal to an entire wave-length.

The location of the sound was determined by the phase differences at the two ears. "The intensity of the total impression showed several variations during a period; a distinct maximum was observed at the first median location, another at each of the two lateral localizations, and many times a weak rise of intensity at the second median position."

He then put two slightly mistuned forks, one at each end of a tube, as in Rayleigh's experiment. With a period of 1 per 5 seconds to 1 per minute between the forks, the sound traveled back and forth, accompanied by a gradual rise and fall of intensity. "The tone moved from the side of the lower tone, with a gradual rise of intensity, toward the median plane, from there it goes to the side of the higher fork with a gradual decrease in intensity. But before the sound had entirely reached this side it began to grow in intensity, and reached a second maximum when it had just about reached the ear. The intensity then again gradually decreased as it
withdrew more to the inside of the head, where it became uncertain, and seemd to cover the entire line connecting the ears. This state is of short duration. The tone, with increased intensity, then suddenly appears on the other side, where the intensity again slightly decreases, and as it again approaches the median plane the intensity also increases." With low frequencies the strongest maximum seems to be that of the median localization, but by greater frequencies the maximums at the sides are of greater intensity. With very weak tones the uncertain period becomes one of silence.

Another experiment which Rostosky carried out was the placing of the stems of the mistuned forks at corresponding points on opposite sides of the median plane. The same effect as in the previous experiments were observed. When the forks were moved nearer to the median plane, the sound did not move so far from the middle. When certain corresponding points on the head were reached, the sound did not leave the median at all, but when the forks were brought still nearer to the median, the sound again began to move out to the sides, but in the reverse direction.

Rostosky thinks that the localization is ultimately due to intensity relations. He assumes in his explanation that there are two separate interferences and consequently two points at which the interference takes place.
This interference must be dissynchronous if it is to have the lateral effects. He assumes further that each tone travels two ways which vary in acoustic length. The mechanical parts of the two auditory organs constitute the two points of interference. The two paths which each tone travels are assumed to be (1) the way from the vibrating part of the ear to the nerve ending of this same organ; the second is the way through the head, especially through the skull to the opposite ear. These two ways, as stated above, he assumes to have different acoustic lengths. With these assumptions Rostosky shows that a change in phase between the two ears, as is brought about in his experiments, will result in intensity relations at the points of interference, which will determine the observed localization of the sound.
EXPERIMENTAL

The purpose of these experiments was to make a more detailed study of the rotary and lateral effects observed by men who had made previous investigations in this field.

The first series was carried on in the research room of Professor Stewart. He had made previous investigations in this field and had suitable apparatus arranged for the present experiments. The present experiments were planned and arranged by him, the writer assisting in making the observations. It is through the kindness of Professor Stewart that the data here obtained was used in this investigation. It was the aim in this series of experiments to make a more detailed study of the rotary effect observed when there is a continual change of phase at the two ears.

The remainder of the experiments were made in the Psychological Laboratory of the State University of Iowa under the supervision of Dean Seashore. They had as their aim further investigation into the nature and cause of the change in localization with a change in phase-difference at the two ears.
Experiment I

The apparatus consisted of two tuning forks, about 100 vd (aa'), Fig. 1, mounted about 2 feet apart on iron bars (bb') which in turn were mounted on a heavy iron base (c). Between this base and the table (d) upon which it rested a heavy layer of felt was placed to prevent vibrations of the wood in the table. Upon the heavy iron base a number of very heavy pieces of iron were laid which absorbed practically all of the vibrations of the iron base. One of the forks (a) was mounted in a horizontal and the other (a') in a vertical position; the reason for this arrangement will be seen later. Each fork was electrically maintained, and by means of resistance in the circuits the amplitude of each fork could be regulated at will. Near one of the prongs of each fork was placed the end of one of the rubber tubes (ee'). These tubes were of equal length and acted as conductors of the sound from the fork to the ears, one tube leading the sound from one fork to one ear, the other leading the sound from the other fork to the opposite ear. The sound was led into the ear by means of small hard rubber tubes (f) which fit into the ear openings. By means of weighting
the prongs of one of the forks its frequency could be lessened so that any desired period between the two forks could be obtained. Consequently a continual change of phase took place at the ears.

The relation of phase was objectified so that the experimenter could always see in what phase-relation the two forks were to each other. This was accomplished by arranging an apparatus so as to get the Lissajous figures (described by Everett in "Vibratory Motion of Sound, p. 67), on a screen.

The intensity at the two ears was varied by moving the end of the tube nearer or farther away from the prong of the fork. In this way the amplitude of the fork itself was not changed.

Series I

1. The first group of experiments in this series was carried on with four practiced observers. They were conducted in a somewhat promiscuous way so as to get a general view of the effects that could be obtained by changing the conditions. The period between the two forks was from 15 to 30 seconds in duration, and the sound from the faster fork was in the left ear. Observations were made with various intensity relations at the two ears. The observer would speak the position of the sound when it reached the
points directly in the median plane and when the sound was farthest to the sides. The experimenter made a record of the phase-difference at which the localization at these four points occurred. This could be done with reasonable accuracy by watching the figure on the screen, and recording it as seen in Fig. II, which shows parts of such records. In these records two of the oblique lines represent one period or cycle. The two opposite ends of the lines represent the phase-differences of 0° and 180°, while the middle points on these two lines represent differences of 90° and 270° respectively.

It was found that the rotary or lateral effects were not obtained by all. The majority of observers, however, would get the effect at once or with a little practice. Those who could not get the change in location were not defective in hearing, neither was their ability to localize sound defective.

When the left fork was the faster the sound went from the middle at 0°, to the left at 90°, back to the middle at 180°, to the right at 270°, and then back to the middle at 0°. When the right fork was the faster the direction of the sound was just the opposite.

For the observers who obtained the lateral effects, the change of intensity at one of the ears did not do away with the effect, although in some cases it was less
prominent at the side on which the sound was weakest, but the phase-relation in which the four locations were made was usually shifted somewhat. This fact will be dealt with more in detail in the next group.

The sound was practically always found to be clearest and most distinct when the phase-difference was 0°. Following are some of the introspections on this point.

"The sound in front is best heard."
"Sound is clearest in front."
"Sound clearest in front."

In these cases front was at 0°.

The sound at the back, or at phase-difference 180°, was usually observed to be indistinct and diffuse.

Of the cycle as a whole the part from 270° to 90° was usually recognized as the clearest and most distinct, as is shown by the introspections --

"Sound from right to left is best."
"Right to left is best."
"Get the sound best going from right to left."

As to the direction in which the sound moved, it always took place in the above mentioned way, but the locations of the 0° and the 180° were with some observers interchanged; in this case the sound at 0° would be located back of the aural axis and 180° in front. Here, of course, the direction of the sound was seemingly reversed.
In another case the sound traveled from one side to the other just back of the head; in this case no localization in front was observed.

It was also observed that the intensity varied during the cycle. This point will be considered more in detail in the next group.

The distance of the sound from the head also seemed to vary in some cases.

2. A group of experiments was arranged with the purpose of gaining more evidence concerning the following points:

(1). The point of maximum intensity, and its degree relative to the minimum.

(2). The rotation of the sound. (a) Whether it reverses when the forks, with respect to the two ears, are exchanged. (b) The distance the sound travels from the head.

(3). The influence that change of intensity at the two ears has.

(4). What influence the length of the period has upon the results in this experiment.

a. To determine the point of maximum intensity the observer said "now" when the point of greatest intensity had been reached. In this way each observer gave about fifteen judgments. This was done for periods of 15, 5,
and 30 seconds. At this time the observer was also asked to make a comparison as to the intensity of the maximum to the intensity of the minimum in the period. This, of course, could be done only with an approximate degree of accuracy, since there was no definite standard of judgment.

The results for the determination of the maximum are shown graphically in Fig. III. The circles 1, 2, and 3 represent the periods of 15 seconds, 5 seconds, and 30 seconds, respectively. The radii represent the phase-difference between the two forks. The black dots show where the maximum was located for each period.

We find here that the maximum, except in two cases in Observer I, fall between a phase-difference of $90^\circ$ and $230^\circ$; or in that place where the two sounds are in the greatest opposition. This is contrary to what one would naturally expect.

The length of the period of rotation apparently does not affect any definite change in the point at which the maximum is placed, except that there may be a tendency to place the maximum in the 5 second period at a greater phase-difference. This may be due to a certain extent to the rapidity, more time being lost in taking the record.
Observer I = x
Observer II = o
Observer III = •
Observer IV = ∆
The comparison of the intensities gave the following judgments. For the 15 second period Observer I had no standard for judging, but said that the "maximum is considerable louder" than the minimum. Observer II judged the maximum to be about two times as loud as the minimum. Observer III said it was louder but could not judge exactly; and Observer IV gave the same answer as III. For the 5 second period the following judgments were given:

Observer I - "Maximum probably two times minimum"
Observer II - "Maximum about two times minimum"
Observer III - "Maximum one and one half times minimum"
Observer IV - "Maximum two times minimum."

For 30 second period:

Observer I - "Maximum about two or three times minimum"
Observer II - "Maximum about two times minimum"
Observer III - "Maximum about one and one half times minimum"
Observer IV - "Maximum about two times minimum."

Apparently there is not much change in the comparative intensity of the maximum in the three different periods.

b. The direction of the rotation when the two tones are exchanged was determined by exchanging the ear tubes. In
connection with this the observer was also asked to state as nearly as possible the distance that the sound traveled from the head.

When the ear tubes were exchanged, thus putting the faster fork in the right and the slower fork in the left ear, the sound reversed in direction in every case. This indicates that the direction in which the sound travels is determined by the ear to which the forks (faster or slower) are led.

As to the distance from the head that the sound travels, the following judgments were given. For 15 second period --

Observer I - "Sound travels back and forth just back of the head"
Observer II - "In front sound travels just over the forehead, and through the head in the back"
Observer III - "Sound about two feet from head"
Observer IV - "It travels in a circle about two feet from the head in front".

For 5 second period --

Observer I - "Sound travels around the head"
Observer II - "Sound travels farther in the head"
Observer III - "Travels about one foot from head"
Observer IV - "Travels about two feet from head in front".
For 30 second period --

Observer I - "Sound is about six inches from back of head and from eight to twelve inches in front of the head"

Observer II - "Sound travels in the head"

Observer III - "Travels about four feet from the head in front"

Observer IV - "Travels about two feet from the head in front"

In observer III there is an increase in distance from the head with an increase in the length of the period. For the other three observers the distance remains about constant; at least there is no proportional increase.

These same results are represented graphically in the diagrams, Fig. V.

c. To find the influence of intensity at the two ears upon the judgment of sound localization, six different combinations of the intensities at the two ears were made. Each observer gave 15 judgments in each of the three periods on each of the six combinations. To make this as simple as possible for the observer, he was asked to locate only the one middle 0° at which place the sound was clearest and
most distinct. The combinations were as follows, the number of millimeters representing the distance of the glass tube from the prong, R and L standing for right and left respectively:

A (1. L = 20 mm.; R = 5 mm.
(2. L = 20 mm.; R = 20 mm.
(3. L = 20 mm.; R = 35 mm.

B (1. L = 20 mm.; R = 5 mm.
(2. L = 5 mm.; R = 5 mm.
(3. L = 5 mm.; R = 20 mm.

An estimation of the comparative relation of these intensities gave the following results:

L. 20 mm.: R. 5 mm. = 2 : 1
L. 5 mm.: R. 5 mm. = 1 : 1
L. 5 mm.: R. 20 mm. = 1 : 2

In A the intensity in one ear was kept constant, while the other was increased from a less to a greater intensity than the constant one. In B the right side was less in intensity; the left was then reduced to equality with the right; after this the right was made greater than the left.

The results obtained are shown in the following tables. In these tables the numbers represent the degree of phase-difference between the two forks at which the sound seemed
### Group A

<table>
<thead>
<tr>
<th>Observer</th>
<th>15 sec.</th>
<th>30 sec.</th>
<th>60 sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.20 m.m.; R &amp; h.m.</td>
<td>60° 70° 85° 315°</td>
<td>75° 60° 70° 315°</td>
<td>70° 10° 50° 285°</td>
</tr>
<tr>
<td>&quot; 20 &quot; ; &quot; 20 &quot;</td>
<td>350° 250° 90° 310°</td>
<td>30° 150° 95° 295°</td>
<td>22° 25° 75° 285°</td>
</tr>
<tr>
<td>&quot; 20 &quot; ; &quot; R35 &quot;</td>
<td>5° 23° 80° 0°</td>
<td>75° 40° 90° 315°</td>
<td>22° 15° 15° 305°</td>
</tr>
</tbody>
</table>

### Group B

<table>
<thead>
<tr>
<th>Observer</th>
<th>15 sec.</th>
<th>30 sec.</th>
<th>60 sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.20 m.m.; R &amp; h.m.</td>
<td>25° 67° 60° 355°</td>
<td>85° 10° 40° 300°</td>
<td>22° 15° 40° 295°</td>
</tr>
<tr>
<td>&quot; 6 &quot; ; &quot; 5 m. h. &quot;</td>
<td>5° 45° 30° 345°</td>
<td>10° 13° 30° 300°</td>
<td>10° 0° 45° 335°</td>
</tr>
<tr>
<td>&quot; 6 &quot; ; &quot; in 20 &quot;</td>
<td>32° 33° 15° 335°</td>
<td>337° 0° 60° 300°</td>
<td>337° 20° 25° 300°</td>
</tr>
</tbody>
</table>
to be located in the median plane. These same results are represented graphically in the diagrams Fig. IV. The diagrams 1, 2, and 3 represent the three periods. The inside circle in each one represents the intensity relation as given above under A1, the middle circle A2, and the outer one A3. The same representation is true under B.

In the combinations under A there apparently does not seem to be any well defined tendency for the location to shift with the change of intensity, except that in observers I and II the phase difference at which the front is located shifts somewhat from a greater to a smaller phase-difference. In B there is a fairly well defined tendency for the location of the sound to shift from the right to the left.

There is no well marked difference between the results of the three different periods. The judgments in the 5 second period are probably not as exact as the others, due to the rapidity with which the sound changes. The fact that most of the localizations are to the left of 0° may be due to the fact that by the time the judgment was given the phase-difference as represented on the screen was greater than when the subjective judgment was made.
A

Observer I = X
Observer II = o
Observer III = •
Observer IV = △

Inside circle = L.20 m.m.; R.5 m.m.
Middle circle = L.20 m.m.; R.20 m.m.
Outside circle = L.20 m.m.; R.35 m.m.

B

Inside circle = L.20 m.m.; R.5 m.m.
Middle circle = L.5 m.m.; R.5 m.m.
Outside circle = L.5 m.m.; R.20 m.m.

Observer I = X
Observer II = o
Observer III = •
Observer IV = △

Fig. IV
c. In this experiment the observer was asked to listen for three periods of 5 minutes each and describe at the end of each period what he had experienced. Ample time was given between periods to prevent fatigue. The length of the period between the forks was about 10 seconds. If any rotation was observed the observer was asked to describe this more in detail. To make sure, in case no rotation was mentioned, that no rotation was noticed, the observer was asked after the third period whether any effect of this kind had been observed.

The introspections given by twenty-three observers are as follows.

Observer I

1st period. "Got beats. Crest seems to grow lower and lower. Seemed to start out loud in right ear; then went down; started louder in the other"

2d period. "Still has beats. Not so noticeable toward last as first"

3d period. "No beats; sound seemed to be constant."

Observer II

1st period. "Heard prominent beats and a small secondary beat. Sound seemed to go from one ear to the other as beats occurred."
2d period. "In right sound seemed louder. Seemed to go from one ear to the other with beats. Beats same as before."

3d period. "Seems to go from right to left quicker than the other way. Sound travels in circle just over face. Seems equally distinct all way round. I observed this circle in 1st and 2d period, but not distinctly. Right and left loudest." For him the sound seemed to travel an equal distance from the head all the way round.

Observer 3.

1st period. "There was a deep rumbling sound which increased and decreased in intensity rhythmically; then there was a kind of ringing sound."

2d period. "Same as before only seemed to lose the rising and falling if did not observe closely."

3d period. "No change."

Observer 4.

1st period. "Sound seems to fluctuate, seems to move partially back and forth back of the head with the fluctuations. Seem to be two sounds, one kind of buzzing sound in head."

2d period. "Seemed to notice another real high tone, seems to come from back of the head. Otherwise as before."
3d period. "Tone seemed to be more persistent, not so much fluctuation. Didn't notice moving of sound much any more. Never distinct."

Observer 5.

1st period. "Sound first seemed to be up on top of forehead; seems to move in a kind of wave like way back and forth through about 4 - 5 inches. Then I paid attention to left ear and sound seemed to be just back of head and stationary."

2d period. "Sound stable, seems to be a kind of bell sound in left ear."

3d period. "Sound seems to be stable in back, seems to move a little some times and seems to be a little louder."

Observer 6.

1st period. "First sound seemed to fluctuate; then right ear sound seemed to overcome left ear sound"

2d period. "Sound seems much stronger in right ear and seems to get louder toward end. I could not notice any fluctuations any more."

3d period. "Just about same as second time; toward last it seemed to be hard to get fluctuation. Right ear is much stronger, especially if attention is given to it."
Observer 7.

1st period. "First noise was loud, gradually got weaker. Has an undertone, also a higher tone. At times seemed to be fluctuations; they sounded like rings coming about so often."

2d period. "Didn't hear ringing sound; sound seemed to rise and fall; sound seemed to be mostly in right ear; tone seemed louder when I inhaled air. Sound seemed to be in median plane some of the time."

3d period. "Sound would rise and go down irregularly. Sound seems to go when loud in left ear over to right ear through back of head and fade away in right ear; then would begin in left ear again."

Observer 8.

1st period. "Very loud at first, then got quiet; seemed to hear first in one ear then in the other; then in both at times."

2d period. "Same variation in sound; sound seemed as one; seemed to be a constant increase or decrease, seemed to come in left and go out at right. On the whole sound seemed louder. The vibrations in ears could be noticed; then stopped at intervals of about 10 - 20 seconds. "As far as I could tell, sound went straight through head. Did not hear this the last time. Second time seemed to be very indefinite. Just seemed to be in one ear, then in the other."
Observer 9.

1st period. "Seems to be a kind of roar; sound grows louder and weaker."

2nd period. "Sound more of a hum. Wasn't so intense; hum is in the head."

3rd period. "Just a hum; were fluctuations in sound."

Observer 10.

1st period. "First sounded like a steady roar in right ear. Seemed to be a fluctuation in the sound, a rise and decrease."

2nd period. "Sound seemed to be more in back of head. Still noticed those recurrent intervals."

3rd period. "Seemed as if sound was more in left ear. Intervals seemed to come faster. Seemed to move back and forth back of head. Seemed louder when it went to the left ear than when it went from it."

Observer 11.

1st period. "First loud roaring sound. First were also sort of ticking sounds; these died out. Sound seemed to be sort of diffuse. Couldn't localize. Couldn't tell just where it came from."

2nd period. "Little ticking noise seemed to be in left ear; didn't die out; other noise got weaker."
3d period. Ticking noise pulsated; other got to be a loud deep ringing sound. Couldn't localize."

Observer 12.
1st period. "Sound seemed to be in back of neck. Kind of a humming sound."
2d period. "Seems about same; sound is in same place."
3d period. "In right ear beats seem to occur regularly but faintly. Sound seemed to be in same place."

Observer 13.
1st period. "Sound went from one ear to other; sometimes tones were different than at others."
2d period. "Sound seems to be high in pitch on left side and go low on right side. Sound moves from one side of head to the other."
3d period. The sound for this observer goes from the right ear "right over back of head" where it was quite distinct; from the left ear it went through the head, where it was indistinct.

Observer 14.
1st period. "Sound seemed to go from right to left regularly. Grew louder and fainter."
2d period. "Sound grew louder and weaker; seemed to move from right to left ear."
3d period. "The same circuit of (high and low ?) and shifting of sound." The sound went from left to right just in top of head, and from right to left just under the head. It was less distinct on top and most distinct just under the head.

Observer 15.

1st period. "Sound seemed to travel from one side to other; seemed to be higher pitch on right side."

2d period. "Facts seem about the same, only sound seemed to be stronger at each ear than at other places. Pitch constant."

3d period. "About the same as other time." The sound for this observer travelled in a circle about equidistant from the head. The most distinct points were on the right and left, but not much difference between the fronts.

Observer 16.

1st period. "Seemed to fluctuate stronger at times; seemed like one sound."

2d period. "Seemed like two sounds, one was an undertone; no fluctuation. Sound seemed to be more in left ear."

3d period. "Sound seemed to be same in both ears; no fluctuations."

Observer 17.

1st period. "Sound seemed to begin at left ear, then go to right; when it came back to left it seemed to swell
and retard, sometimes seemed to be all on one side then on the other."

2d period. "Seemed to be a sort of periodic disturbance; first loud then soft; sound seemed to move somewhat."

3d period. "Last the same, only tone seemed heavy."
The sound from left to right through the top of the head. From right to left it went through the head from ear to ear. In this latter place it was most distinct.

Observer 18.

1st period. "Sound in each ear, then made one sound. Sound sometimes seemed to be at end of nose, then back of head. Seemed to be about three sounds."

2d period. "Sound seemed to travel persistently from one ear to the other."

3d period. "Same motion of sound; seemed to be several others enter in." The sound traveled from right to left through the top of the head, where it was the most distinct. From left to right it went along the aural axis, where it was most diffuse.

Observer 19.

1st period. "Sound seems to fluctuate, rise and fall; later seemed to be a bell-like sound coming at regular intervals."
2d period. "Same tone, remained more constant."
3d period. "Same as in 1st and second."

Observer 20.
1st period. Seems to be a beat; has same pitch and same loudness; sounds like one sound."
2d period. "Seems like one sound, one deep continuous, other higher and had beats." 3d period. "Seemed to notice beats more than other time."

Observer 21.
1st period. "Seemed to grow in intensity in right ear; was a kind of metallic sound in left ear." 2d period. "Sound seemed to go from right to left with maximum in front."
3d period. "Shifting seemed to cease sometimes."

Here the sound travels from right to left in front where it is most distinct, from left it passes directly through the head to right; in this latter part of the rotation it is most diffuse.

Observer 22.
1st. period. "Loud sound seems in left ear."
2d period. "Sound seems to travel from right to left; takes about 3 - 4 seconds to go from right to left back of the head."
3d period. "Still get shift."
The sound travels from right to left back of the head, and from left to right directly through the head. It is most distinct in the back, and very indistinct in the head.

Observer 23.

1st period. "Sound seemed to be louder and weaker; this occurred regularly."

2d period. "Noticed nothing different; still noticed rising and falling of sound."

3d period. "Heard a kind of metallic sound once in a while; still noticed rising and falling of sound. Sound seemed to be at the same place all the time."

These results show that out of the 23 observers 10 got no rotation or lateral effects at all. Two got a partial rotation. 11 got the whole rotation, that is, the sound was located on one side and then on the other alternately. Thus we see that only about one half of the observers get the distinct rotary or lateral effects.

Of the 11 observers who got the whole rotation, all but one, or possibly two, recognized a difference in distinctness between the halves of the rotation. In almost all these 11 cases the sound in one half was more diffuse and indistinct than in the other.
Seventeen out of the twenty-three mention the fact that they hear beats or fluctuations. A number also heard secondary noises. These may be due to a little sound made by the contact of the forks, but in some cases, however, it did not seem to be the noise made by the contact.

Six of the eleven observers who got the whole rotation got it in the first period; three in the second period; and two in the third period. Practice evidently does not play a large part in ability to get the rotation. This is further substantiated by the fact that several observers who were told of the rotary movement of the sound were not able to get it even with considerable practice.

Series II.

The following experiments were made to determine (a) how small a difference in the relative length of the tubes made a perceptible change in the localization, (b) whether the sound localization is better in or near the median plane than at the side, and (c) what difference, if any, the vibration frequency of the source makes in the above mentioned factors.

The apparatus used in this experiment is in principle the same as that used by Wilson and Meyer. A diagram of the apparatus is shown in Fig. 5.
Tuning forks of 128, 256, 512, and 1048 v.d. were used as sources. The forks were presented by hand. The experimenter was hidden from the view of the observer by a screen which stood between the experimenter and the observer.

The sound moved from one side to the other as the T piece was slid from the center farther and farther to one side. When the T piece had been moved through a distance of about 1/8 of a wave-length to one side, making a difference of 1/4 wave-length between the two tubes, the sound was farthest to the side; when it was moved another 1/8 wave-length in the same direction, the sound again was located in or near the median plane. A movement of another 1/8 wave-length brought the sound to the opposite side; and a farther displacement of another 1/8 wave-length, which made a difference of about 1 wave-length between the tubes, brought the sound back to the middle. These results, as so far stated, agree with those obtained by Wilson and Meyer.

The sound with the 128 and 1048 forks/a source] first moved to the side of the longer tube. With the 256 and 512 forks the sound started out in the opposite direction. Considerable time was spent to find out why the 128 and 1048 forks did not produce the same results as the other two
forks. Various changes were made in the apparatus with no change in the results. Finally a new sliding T piece was made which was exactly the same as the one already used except that the opening in it was divided into two parts so that the sound going to the separate ears could not interfere with each other. When this slide was used, the same results, so far as direction in which the sound moved was concerned, were the same as those obtained with the other forks. The records of the experiments here given were taken before this second slide was made. The localization of the 128 fork thus started out from the head directly opposite to the 256 and 512 forks. Just what causes this change is not yet known, but it apparently is a change brought by the reflection or interference of the sound in the tube. The contrary action of these forks, when the slide is divided and when it is not, is of importance in that it shows that occurrences external to the head may at least change the direction of the sound. This presents a problem which remains to be worked out.

To find out with what accuracy a sound in the median plane was located, the experimenter gave first a sound at the center point; the T piece was then moved a certain
distance either to right or left (the direction being determined by a key in which the directions were chosen arbitrarily); the observer then judged the direction in which the sound had moved. When the distance was found with which the observer got from 65 to 85% of the judgments correct, 100 judgments were made. The distance for 75% correct judgments was then found by means of the Fullerton and Cattel table. (Sanford's, Experimental Psychology, p. 354). In this way 100 judgments were taken with the sound in the middle and 100 with the sound at the side. This was done with the forks 128, 256, and 512 as sources. 200 judgments were then taken for each fork by each observer. Three practiced observers assisted in making these observations.

The results of these experiments are given in the following table. Column 1 contains the vibration number of the fork; column 2, the reading on the scale at which the standard or first sound of each pair was given. These, in column 1, were of course all given at 0. Column 3 gives the change in length between the two tubes, in centimeters, with which change 75% correct judgments would be obtained. Column 4 gives the difference in parts of the wave-length of the source. Column 5 contains the standard position at the side. This position is not at the point where the sound is farthest to the side but a little before
<table>
<thead>
<tr>
<th>Observer</th>
<th></th>
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<th></th>
<th></th>
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<tr>
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<td>6 cm</td>
<td>1.4 cm</td>
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<tr>
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<td>0.18</td>
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<tr>
<td></td>
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<td>0.7 cm</td>
<td>0.11</td>
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<tr>
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<td>0.17</td>
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<td>20.3 cm</td>
<td>0.76</td>
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<td></td>
<td>25.6</td>
<td>0</td>
<td>2.2 cm</td>
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<td>13 cm</td>
<td>4 cm</td>
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<tr>
<td></td>
<td>51.2</td>
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<td>0.15</td>
<td>6 cm</td>
<td>2.1 cm</td>
<td>0.032</td>
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</tbody>
</table>
it so that the sound still moves off to the side when
the source is moved beyond the standard. Column 6
gives the change in length of the two tubes, in centimeters,
with which change 75% correct judgments are obtained with
the sound at the side. Column 7 gives the difference
in parts of the wave-length of the source.

These results show a certain degree of individual
difference, which may, of course, be expected. These dif­
ferences on the whole are not very large. The 128 fork
was in all cases more difficult to localize than the 256
and 512 forks. The latter were localized with the same
degree of accuracy. The sound at the side is more dif­
ficult to localize than when it is at the center. The
ratio between the differences is almost as 1 : 2.

The fact that the 128 fork was more difficult to lo­
calize than the others is possibly due to the same cause
as that which makes the sound move in the opposite direc­
tion. For, when the divided slide was used, one observer
was able to localize the 128 fork with greater accuracy than
the 256 and 512 forks. In this case the difference in
length of the tubes was 1.36 cm., and the difference in
parts of wave-length .005. This also needs further inves­
tigation.

In these experiments it was essential to keep the con­
tacts at the ears the same, for if one contact gave the
sound wave an opportunity to escape it made a decided difference in the localization.

Experiments were next carried on with a simplified apparatus, the purpose of this being to verify the results obtained with the apparatus previously used.

The apparatus consisted of two rubber tubes which were used as conductors. The contacts with the head were hollow wooden discs of such size that they fitted around the outside of the ears. That part of the disc which came into contact with the head was padded with hollow rubber tubing so that the contact fitted tight against the head to prevent diffraction of the sound wave. To obtain equal pressure of the opposite sides, the two discs were connected by means of rubber bands which would draw the two discs against the head with equal pressure. The other two ends of the rubber tubes were connected by means of a Y tube. At the open end of this tube the source was placed. The source in all cases was a 128 v.d. tuning fork. Usually this was presented by hand. In some cases it was maintained electrically. The length of the tubes was varied by inserting or taking out pieces of tubing of the same size.

The writer acted as one of the observers in most of these experiments, since it was found that the results were
not changed by a knowledge of the experimental conditions. The other observations were made by two experienced observers.

First a number of experiments were made to determine whether the same lateral effects were observed if the phase is changed in one ear only. In this case the length of the tube in the left ear was made equal to one wave-length and kept constant in length, while the length of the tube leading to the right ear was changed by shortening the tube by quarter wave-lengths. In the following table some of the records made by two observers are shown. The sequence of the relative lengths were chosen arbitrarily.

<table>
<thead>
<tr>
<th>Relative lengths</th>
<th>Observer I</th>
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</thead>
<tbody>
<tr>
<td>L, 1 ; R, 3/4</td>
<td>L M L M L L</td>
<td>L L L L L L</td>
</tr>
<tr>
<td>L, 1 ; R, 1/2</td>
<td>M M M R R L</td>
<td>M M M M M M</td>
</tr>
<tr>
<td>L, 1 ; R 1/4</td>
<td>L L L L L L</td>
<td>L L L L L L</td>
</tr>
</tbody>
</table>

In practically all of the observations made under these conditions the sound went from the middle to the left, back to the middle, then instead of going to the right it went back to the left side. Thus only the one lateral effect was obtained and not the opposite alternate effects.
When both tubes were varied the alternate opposite lateral effects were again observed.

Another experiment was made to determine whether the results would be the same when the sound entered the tubes with a phase difference of 180° while the relative lengths were the same as in the former experiment. The difference in phase was obtained by placing the ends of the two tubes on opposite sides of a disc attached to the pring of an electrically maintained fork. Both tubes were varied; that is, to get a quarter wave length difference one tube was shortened an eighth and the other lengthened an eighth of a wave-length. Following are some of the results.

<table>
<thead>
<tr>
<th>Relative Lengths</th>
<th>Observer I</th>
<th>Observer II</th>
<th>Observer III</th>
</tr>
</thead>
<tbody>
<tr>
<td>L, 9/8; R, 7/8</td>
<td>L L L L L</td>
<td>M M L L L</td>
<td>L L L L L</td>
</tr>
<tr>
<td>L, 10/8; R, 6/8</td>
<td>M M M M M</td>
<td>M L L L L</td>
<td>M M M M M</td>
</tr>
<tr>
<td>L, 11/8; R, 5/8</td>
<td>R R R R R</td>
<td>M R R R R</td>
<td>R R R R R</td>
</tr>
</tbody>
</table>

The lateral effects are the reverse of those obtained when the sound enters both tubes in the same phase. The phase difference for 9/8 - 7/8 and for 11/8 - 5/8 when the sound enters the tubes with a difference of 180° is exactly the same at the ears as in the combinations 11/8 - 5/8 and 9/8 - 7/8 respectively when it entered the tubes in the same
phase. These results apparently indicate that the lateral effect depends upon the phase relations.

Further, an attempt was made to determine how small a change in intensity will affect the localization. This was done by means of putting small holes two millimeters in diameter into the tube next to the wooden disc. These holes could be opened and closed at will. There is one objection to this method, namely, that the wave as it passes the open hole is probably somewhat changed.

The results in this experiment show that a difference in intensity which can scarcely be detected by putting the tubes in the ears alternately is sufficient to move the sound from a lateral position to the middle or from the middle to the side. This indicates that the cause for this localization is a small one and is easily overcome by other factors. This is further substantiated by the fact that a very small difference in the position of the contacts will cause a change in localization. Another test that can be made to test the intensities at the two ears is to measure the intensities at the contacts in some empirical way.

The relative intensities of the sum of the sound at the ears for the different combinations was determined by
attaching both ends of the variable tubes to two Y tubes. At one Y tube the source was placed, the open end of the other Y tube being attached, by means of a rubber tube, to a third Y tube from which tubes of equal length led to the ears. The sound seemed to be of practically the same intensity when the lengths of the variable tubes were 9/8 - 7/8; 11/8 - 5/8; and 1 - 1/2, but at 10/8 - 6/8 the sound became very faint and sounded far away. This seems to suggest that the sum of the intensity is not determined by the direct waves and their phase relations alone, but that there are other factors which exert an influence.

Conclusion

The results of this last series of experiments are not sufficient to warrant any definite conclusions, but they present many problems which must be solved before any such conclusions can be reached.

The results obtained from the present experiments as a whole are not contradictory to those obtained by other workers in this field. In fact, the present work substantiates most of the observations made by these men. Apart
from this the present experiment brought forth several new factors; it shows some new elements which must be taken into account; and also, through the various means and methods used, it suggests other probably more crucial methods of attack.
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