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On the Perception of the Direction of Sound.

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The following paper contains an account of a series of experiments on the perception of direction of sound which were undertaken with the object of investigating the nature of the influence of phase differences between the vibrations at the two ears. Lord Rayleigh* has shown that such differences help to determine the apparent direction of the sound, the sound appearing to be on the side at which the phase is the more advanced. Professor More† arrived at a similar conclusion to Lord Rayleigh by experiments of a different character. The following paper also contains a theory of the influence of phase differences which appears to offer a possible explanation of the observed effects.

Most of our experiments have been done with an apparatus similar in principle to Professor More's, but permitting of a continuous variation of the difference of phase. The apparatus consisted of a brass tube, AB (fig. 1), about 250 cm. long and 2·5 cm. in diameter, with a short T-piece soldered on to it at its middle point. This tube could slide freely in two slightly larger brass tubes, CD and EF, which were supported horizontally a definite

* 'Phil. Mag.,' February, 1907.
† 'Phil. Mag.,' April, 1907.

distance apart. From the ends of CD and EF wide tubes were led to caps fitting on to the ears of the observer. The tubes were made up of lengths of

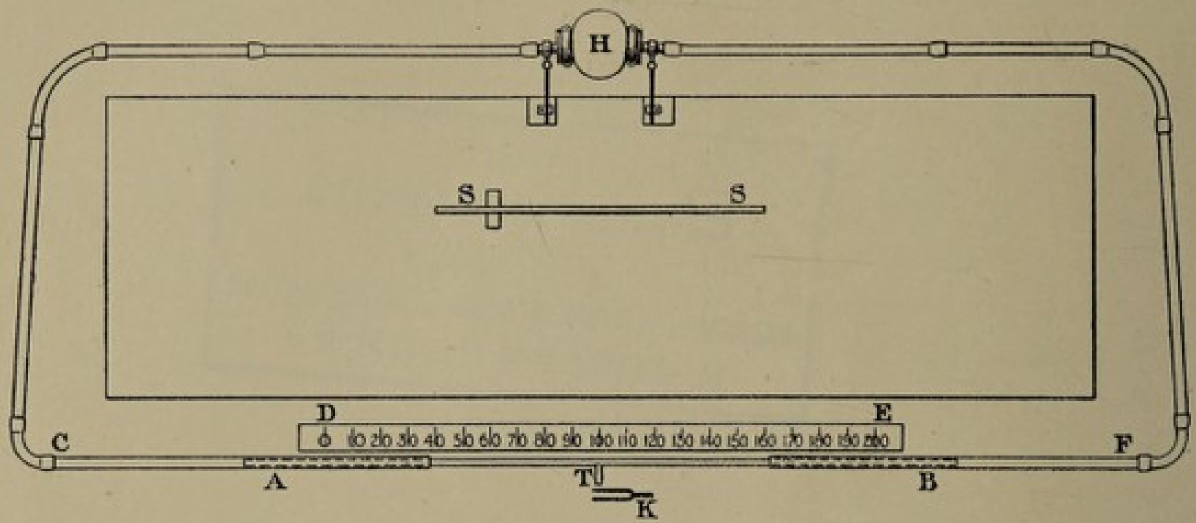

FIG. 1.

AB. Sliding tube.
DE. Scale.
T. T-piece.
K. Tuning fork.
CA, BF. Fixed tubes.
H. Observer's head.
SS. Screen on table.

glass tubing joined together by pieces of wide indiarubber tubing, and the two sides of the apparatus were made as symmetrical as possible. The ear caps consisted of wooden discs with annular soft pads round them which could be pressed against the head. The caps were supported on retort stands clamped to a table, and were adjusted as symmetrically as possible.

A graduated scale was fixed alongside the brass tube AB so that the position of the T-piece could be read off on it. A wooden screen was put up on the table between the observer and the T-piece, so that whichever way he was facing he could not see the position of the T-piece.

A vibrating tuning fork was held near the mouth of the T-piece so that some of the sound from it entered the tubes and went along them to the observer's ears. By sliding the tube AB about, any desired difference could be produced between the paths to the two ears.

Let the distance of the T-piece from the middle point (scale reading 100) of the scale be x cm., and the wave-length of the sound given out by the fork be λ, then the phase difference (α) between the sounds at the observer's ears is $4\pi x/\lambda$. If n is the number of vibrations per second and v the velocity of sound, then

$$\alpha = \frac{4\pi x}{\lambda} = \frac{4\pi n x}{v}.$$

According to Lord Rayleigh's results we should expect that for values of between 0 and $\frac{1}{4}\lambda$ the sound would appear to be in the ear on the right hand side of the middle point, while with x between $\frac{1}{4}\lambda$ and $\frac{1}{2}\lambda$ it would appear to be on the left, and so on for other values of x. If we denote the lateral effect by ϕ, and consider right effects positive and left effects negative, the connection between ϕ and x should be, according to Lord Rayleigh's results, $\phi = A \sin(4\pi nx/v)$, where A is a constant. It would, perhaps, be more correct to say that ϕ should be equal to a Fourier's sine series, of which the above is the first term, but experiment shows that the other terms are probably unimportant, if they exist at all.

One of us acted as observer while the other placed the T-piece in a series of positions, in each of which the observer said on which side the sound of the fork appeared to him to be. A record of the results was kept, and the series of observations was usually repeated. The sensations were usually described as follows :—" Full right," " half right," " middle or half right," " middle," " middle or half left," " half left," " full left." " Half right " meant that the perception of direction was only moderately definite, while " middle or half left " meant that there was only a doubtful perception of direction. " Middle " meant that the sound seemed to come from in front or behind, or that there was no lateral effect.

The following is a typical series of observations :—

Fork 512. Observer facing away from fork.

Scale reading.		
100	M (1)	
105	R (2)	R (26)
95	L (3)	L (25)
90	L (4)	L (24)
110	R (5)	R (23)
85	L (6)	L (22)
80	L (7)	
115	L (8)	L (21)
120	L (9)	L (20)
125	L (10)	L (19)
75	R (11)	R (18)
70	R (12)	R (17)
130	M (13)	L (16)
65	M or $\frac{1}{2}$ L (14)	M or $\frac{1}{2}$ L (15)
135	R (27)	M or $\frac{1}{2}$ R (34)
140	R (28)	R (33)
145	L (29)	M or $\frac{1}{2}$ L (32)
150	L (30)	L (31)

The numbers in brackets indicate the order in which the observations were made.

The results obtained can be conveniently represented by means of curves whose co-ordinates are the scale readings showing the position of the T-piece and the lateral effects. The lateral effect corresponding to any scale reading was calculated by taking the mean of the observations at that point, counting a "full right" = 1, a "half right" = $\frac{1}{2}$, a "middle or half right" = $\frac{1}{4}$, a "middle" = 0, with equal negative numbers to represent left effects.

Fig. 2 shows one of the curves obtained in this way with a fork of frequency 512. The curve $\phi = \sin(4\pi nx/v)$ is also shown (dotted) and it will be seen that the observations agree with it as well as could have been expected.

Figs. 3 and 4 show similar curves obtained with forks with frequencies 384 and 128.

Fig. 5 shows some of the results obtained with frequency 256.

It will be seen that with frequency 256 the observed and theoretical curves do not agree, in fact the observed lateral effect is just the reverse of that expected.

A good deal of time was spent in investigating the cause of this anomaly and it was finally found to be due to resonance occurring in the tube on one side or the other, according to the position of the T-piece. The observer's ears were replaced by the thin indiarubber diaphragms of two manometric flames, which were observed in a rotating mirror in the usual way. In this way it was possible to compare the amplitudes of vibration on the two sides of the apparatus. It was found that the two amplitudes were always sensibly equal with frequencies 512 and 384, but with 256 there were large differences between the two amplitudes in certain positions of the T-piece. In fact, with this frequency, when the sound appeared to be on one side, there was a greater intensity of sound on that side, which evidently completely masked the phase difference effect. These differences of intensity could be detected, though not very certainly, by listening first at one tube and then at the other.

It was found that the same cause led to the discrepancy between the observed and calculated results with frequency 128 at $x = -60$ (see fig. 4). The lateral effects observed with frequency 256 were of precisely the same character as those observed with frequency 512, although it appears that the 256 effects were due to a difference between the sound intensities at the two ears, while those with frequency 512 were produced by a difference of phase without any difference in intensity.

Some experiments were tried with the tube on one side partially blocked

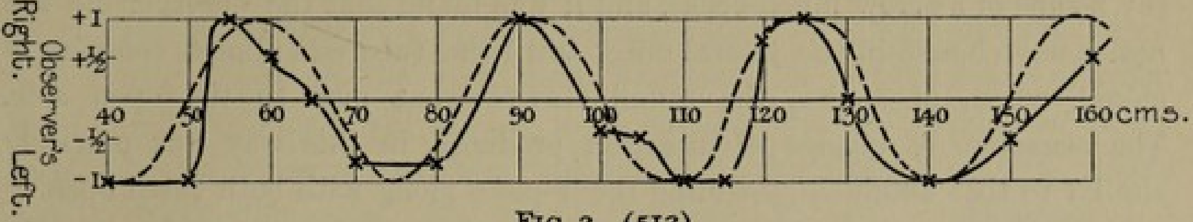

FIG. 2. (512)
(Observer facing towards fork)

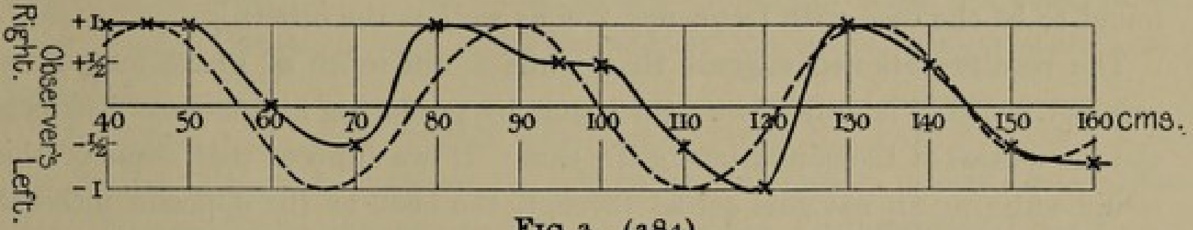

FIG. 3. (384)
(Facing towards)

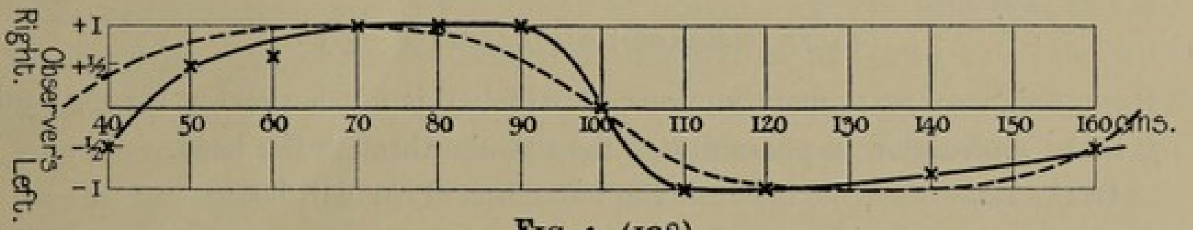

FIG. 4. (128)
(Facing towards)

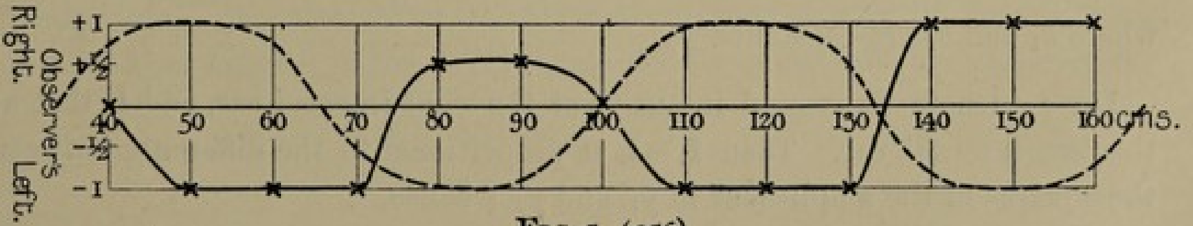

FIG. 5. (256)
(Facing away)

with cotton wool so that the sound on that side was considerably weaker than that on the other side. It was found that the observer, after a time, became accommodated, so to speak, to the difference of intensities, and lateral effects in both directions could then be obtained, although the sound was all the time stronger on one side than on the other.

Experiments were tried in which one side of the tube was gradually closed (by means of a screw pinch-cock), and it was found that the observer did not notice any change in the lateral effect until the tube was almost completely closed, when, of course, the sound always went over to the open side. The sensation of change of direction produced in this way was precisely similar to that obtained by sliding the T-piece along with both tubes open.

Experiments were tried with tubes of different lengths and with the observer facing towards the fork and then away from it, but no very interesting results were obtained. Experiments were also tried with the manometric flames to see if the phase differences calculated actually existed, and this was found to be the case with frequency 256 as well as the others.

The results obtained suggest that while a difference of phase may be a primary cause of lateral effects, yet it acts by producing a difference between the intensities of the sound inside the ears. If we suppose that some of the sound entering an ear gets across through the head to the opposite internal ear, this enables a simple explanation of the phenomena to be given.

Let $y_1 = a\sin(\omega t+\alpha)$ denote the vibration entering the right ear, and $y_2 = a\sin\omega t$ denote the vibration entering the left ear. The resulting effect at the right internal ear will be, say,

$$y_1' = fa\sin(\omega t+\alpha) - ga\sin(\omega t-\beta).*$$

Here f and g are proper fractions, of which f is much greater than g, and β is the retardation in phase due to the passage through the head.

In the same way, the effect at the left internal ear will be

$$y_2' = fa\sin\omega t - ga\sin(\omega t+\alpha-\beta).$$

Hence

$$y_1' = \{f^2a^2+g^2a^2-2fga^2\cos(\alpha+\beta)\}^{\frac{1}{2}}\sin(\omega t+\delta_1)$$

and

$$y_2' = \{f^2a^2+g^2a^2-2fga^2\cos(\alpha-\beta)\}^{\frac{1}{2}}\sin(\omega t+\delta_2),$$

where δ_1 and δ_2 are constants.

Let I_1 denote the sound intensity at the right internal ear, and I_2 that at the left internal ear. Then I_1-I_2 is proportional to the difference between the squares of the amplitudes in y_1' and y_2'; hence,

$$I_1-I_2 \propto 2fga^2\{\cos(\alpha-\beta)-\cos(\alpha+\beta)\} = 4fga^2\sin\alpha\sin\beta.$$

Thus, the difference between the intensities at the two internal ears is proportional to $\sin\alpha$, and if we suppose that ϕ, the lateral effect, is proportional to I_1-I_2, we get $\phi = A\sin\alpha$, where $A\propto 4fga^2\sin\beta$, and so is a constant for sound of a particular frequency.

* We suppose that the displacements in the internal ear due to the two sets of waves are in opposite directions. It should be said that the principal reason for making this assumption is that it enables an explanation of the lateral effects to be given.

Thus, provided $\sin \beta$ is positive, if the phase at the right ear is ahead by an amount between 0 and π, ϕ is positive, that is, $I_1 > I_2$, and the sound will appear to be on the right side, whereas if α is between π and 2π, $I_2 > I_1$, and the sound will appear to be on the left side. Thus, the theory here proposed gives a complete explanation of the observed lateral effects due to phase differences. For very high-pitched notes β would be between π and 2π, and then the lateral effect would be reversed.

The distance between the ears through the head is small, and the velocity of sound through the bones probably very high, so that we should not expect a reversal of the effect due to this cause, unless the frequency were very great. But with very high frequencies the lateral effects cannot be obtained.

The amount of sound which must get through the head to produce an appreciable difference between the intensities at the two internal ears is not large, because since the two amplitudes are added, an imperceptible amount getting through might produce an appreciable difference of intensity.

It was found that an appreciable amount of sound could be sent through a person's head from one ear to the other. Ear caps with tubes attached were fitted to each ear, and a vibrating tuning fork was held near the end of one tube. An observer listened at the end of the other tube, and with a fork of frequency 512 a distinct sound was heard, which seemed to come along the tube. The amount of sound getting through the head must, of course, be much smaller than the amount entering one ear and getting to the opposite internal ear.

The experiments described were carried out in the Physical Research Laboratory at King's College, which has been fitted up with a grant of £500 from the Drapers' Company, to whom, therefore, we wish to express our obligations. We also desire to express our best thanks to Lord Rayleigh for his kind interest in the experiments and for some valuable suggestions.

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