ON DIRECTIONAL HEARING

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BESIDES being able to perceive the sound qualities of height and intensity, man is capable of projecting the perceived sound into space. He can estimate more or less accurately the distance and the direction from which a sound is reaching him. The investigation of this problem was started long ago by physicists and technicians, especially in connection with the stereophony in acoustical engineering, and much information has already been gained.

Briefly for directional hearing in the horizontal plane three factors are relevant namely: the difference of intensity in which the sound reaches both ears, the difference of phase between the tone reaching the left and the right ear, and for discontinuous sounds the difference in time of arrival of the sound at the two ears. For all these factors two organs are required to make directional hearing possible. Indeed it is well known that persons with one deaf ear are hardly able to determine the direction of a sound.

The occurring intensity differences are however only appreciable for high tones. Sivian and White (1) have proved experimentally that the difference is practically zero below 300 Hz. These intensity differences are caused by diffraction phenomena which only occur if the wave length is small compared with the dimensions of the head. Stewart and Hovda (2) found that it was possible to create a directional sensation by presenting sounds with an intensity difference to the two ears. The results were not very steady though and differed greatly from one person to another. However, a logarithmic relation between the angular displacement of the sound image and the intensity difference at the ears could be established and was later corroborated by von Békésy (3). The authors believe that in the natural hearing process the directional sensation is caused by quality differences in complex sounds owing to these diffraction phenomena for the high components.

As the intensity differences are certainly insufficient for an explanation for low tones the phase difference was considered. Rayleigh and Bowlker (4) suspected that the phase influences this process, but Firestone and Wightman (5) proved that it was hardly possible to determine the direction of a pure tone, presented with a phase difference to the two ears.

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Indeed it is very difficult to determine the direction of a sound, consisting of a purely sinusoidal tone, whereas it is much easier for complex sounds. For tones with frequencies above 1000 Hz. no phase effect may be expected because one phase difference would then correspond to many directions. Van Soest (6) moreover demonstrated in an elegant experiment that beside the phase also the intensity must certainly be relevant. A tuning fork is placed on a long rubber tube in various positions. One then estimates how far the sound seems to be displaced to the right or to the left. When the fork is on the left half of the tube a maximal right sensation is never observed, even if the phase difference is such that this might have been expected.

Starting from the observation that the direction of a sound blast, a noise and a complex tone is much more easily determined than that of a pure sine, Hornborstel and Wertheimer (7) arrived at the theory that the difference in time of arrival of the sound at the right and left ear is responsible for the directional hearing. Von Békésy and van Soest and Groot (8) showed in laboratory experiments that a directional sensation really is connected with the time differences varying from a millisec. to a microsec. There is of course much similarity between the theory of time difference of arrival and that of phase difference. The active phase difference is the time difference between two corresponding states of vibration at both ears. Above 1600 Hz. also the time difference theory has to be abandoned, because then even the greatest phase difference corresponds to a time difference too small to permit detection of the sound source in the direction of the produced aural axis.

Finally at present combinations of the above mentioned theories are tried as a solution. For instance, according to Hartley and Fry (9) a combination of intensity and phase difference permits the estimation of the direction and even of the distance of the sound source. De Boer (10) concludes that for human speech 90 per cent. have to be explained by intensity differences and 10 per cent. by phase differences. This author stresses the point that the diffraction of sound by the head depends on the frequency. This dependence causes changes in timbre which may explain some directional hearing even with one ear. Moreover variations in timbre may help the localization in other than horizontal planes and decide between symmetric positions in front and back because of the irregular shape of the skull. Phase and intensity can only restrict the place of the sound source to a rotational cone (11).

According to van Soest (8) and Wallach (11) the exact spot on this cone is determined by small movements of the head.

Such is, briefly outlined, our present state of knowledge. For the physiologist various difficulties arise. Though these theories may be of great practical value and have already yielded important results for modern acoustic engineering, they do not explain in any way the

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physiological directional hearing process. The artificial experiments on directional hearing in the physical laboratories, with differences in intensity and phase cause no directional hearing in the physiological sense. No projection of the observed sound into space is obtained, with an associated directional sensation. On the contrary the sensation is as if the sound is located within the interior of the skull, more or less right or left. This was already observed by the investigators in this field and has given rise to the curious concept (or rather word) " virtual sound-image " (12).

Experiments

We therefore had recourse to the most elementary problem and have investigated from what direction a test person with closed eyes estimates a sound is coming. In order to obtain objective and measurable results we used a graduated semicircle along which the sound source could be moved, and on which the test-person was requested to indicate where he thought the source was situated. For each experiment the subjective place as indicated by the test person was plotted as a function of the objective place, both in degrees as marked on the arc graduation. The experiments were performed in the sound- and reflection-free cellar of the aural clinic of the University of Utrecht. The radius of the semicircle used was 50 cm.

First a number of experiments was performed with various sorts of sound sources, as it was known that the place of origin is determined with varying ease for different sorts of sounds (13). Furthermore experiments were performed mainly in three planes: the horizontal plane, the vertical plane through the ears and the vertical plane through the nose, perpendicular to the former, designated as horizontal, vertical side and vertical front plane respectively. Moreover experiments were performed to eliminate the influence of the auricles by tying them flat to the head or by placing short tubes of about 6 cm. length in the auditory canal. Finally we did some experiments with one ear closed by a piece of cotton wool soaked in paraffin wax.

Sound Source

As a source we used in the first place a telephone emitting purely sinusoidal tones from a frequency generator, operated at a frequency of 4000 Hz., 1000 Hz. or 500 Hz. These tones have a purely sinusoidal character as is shown by experiments with a kathode ray oscillograph. An effort to investigate the localization of tuning forks failed as it was impossible to excite the fork sufficiently to be heard at a distance of 50 cm. without noticeable by-sounds. Furthermore we have used organ pipes, namely a Galton whistle at about 12,000 Hz. an a^3 and an e^2 organ pipe. As a source of a more complex sound we took a watch. Experiments regarding the localization of the human voice with the aid of an

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amplifier were discontinued, as the watch was a perfectly satisfactory representative of a highly complex sound source.

In general we found in agreement with Reich and Behrens (13) that complex sounds, noises and ticking can be localized better than pure tones, especially in the vertical plane. No noticeable dependence on the height of the tone could be observed.

Plane of Investigation

With the experiments in *the horizontal plane*, when the sound source was moved along the semicircle at the height of the ears at a radius of 50 cm. about the centre of the head we constantly found for all sources a good power of localization, at least in the region in front of the test person.

We always observed a slight displacement of the sensation relative to the true source in the direction of the produced aural axis.

Perhaps it is useful to show that the point where the source is believed to be is indicated by the test person with the finger. In a series

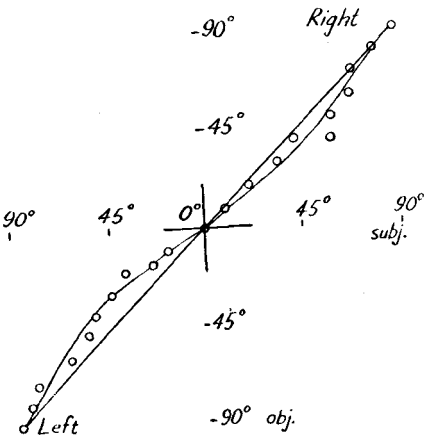


FIG. 1

The curve represents the subjective localization of the sound source as a function of its place in the plane investigated. On the abscissa the subjective place, on the ordinate the objective place of the sound source is indicated. The whole curve covers 180° with zero at the centre. The plane of investigation is horizontal, the sound source a pure sine of 500 Hz. from a frequency generator. The zero is straight in front of the test person.

TYPICAL S-SHAPE

of test experiments this form of indication proved to be very accurate. It was also shown that it was irrelevant which hand (the left or the right one) was used to point at the observed sound source. In this way a curve with a slight S-shape is obtained (fig. 1) for all kinds of sources. However good the localization in front of the test person may be, it is

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very difficult when the sound originates behind him. Besides the difficulty of the indication which may overcome with some patience, the phenomenon of mirrored images appears. Very often a sound originating from behind us is perceived as if coming from the same angle in front. Especially the pure sine gives rise to this misinterpretation. For instance of 13 cases investigated with a pure sine of 1000 Hz., 11 showed mirrored images for all or for the majority of points from the

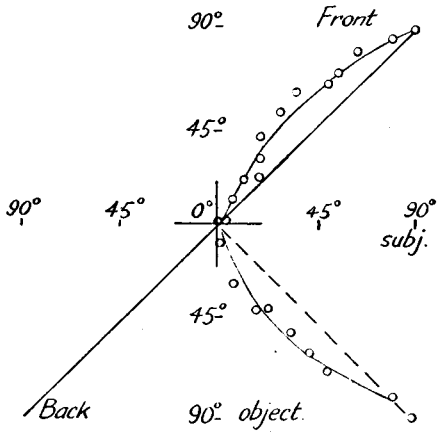


FIG. 2

Plane of investigation horizontal. Source: a^3 organ pipe. Zero point in the direction of the produced aural axis towards the left side. Further data as in Fig. 1.
MIRRORED IMAGE

back to the front (fig. 2). With the pipes this only happened in 50 per cent. of the cases, with the watch only occasionally.

Great care has to be taken not to guide the interpretation by involuntary complex noises such as the breath of the experimenter, crackling of his shirt or suit, for this guidance is utilized immediately, usually unconsciously. Similarly, if one expects a sound to come from a certain direction, then it is indeed perceived from that direction. With some suggestion by the investigator in this way even a mirrored image from front to back side may well be obtained.

The presence of resonance planes has influence. In certain positions the entire mirrored images effect may disappear, for instance when lying on the ground or on a flat table during the observations. So far we could not discover sufficient regularity to draw any conclusions.

In the experiments when the source moved in the *vertical side plane* it was found that with the frequency generator practically no localization was possible. Mostly the sound was heard as if coming from a fixed point, independent of the true place of the source (formation of a sound centre).

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With the organ pipes a good localization was possible, although here too an S-shaped curve resulted, which means that the impression is displaced outwardly i.e. upward and downward (fig. 3). It is curious

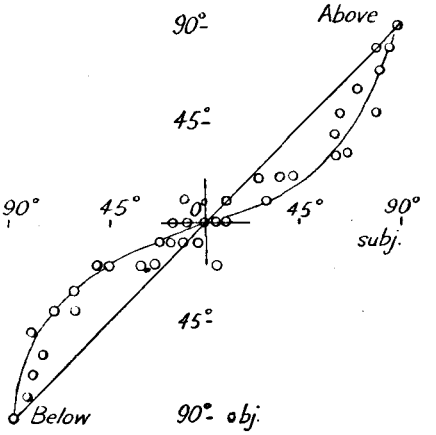


FIG. 3

Plane of investigation: left vertical side plane. Source: e^2 organ pipe. Zero point in the direction of the produced aural axis towards the left side. Further data as in Fig. 1.
PRONOUNCED S-SHAPE AND DISPERSION OF POINTS

that the localization for a high Galton whistle is more accurate than for a low e^2 pipe. A few times a point is reflected relative to the horizontal plane and especially in the neighbourhood of the aural axis (the zero point of the scale) there is often some dispersion. The localization of the ticking of a watch is excellent.

If the semicircle is in the *vertical frontal position* relative to the test person the results are in the main lines similar to those obtained at the vertical side position. Again the localization of the pure sine tone is impossible, whereas pipes and a watch are well localized. Also here sometimes a slight S-shape of the curve is observed, and once in a while mirrored images from above downwards. Moreover a phenomenon is here observed of which a slight suggestion could already be traced with the experiments in the vertical side plane, namely a " compression " of the curve towards the zero point, that means that the sound when coming from exactly above or below, is perceived about 20° in the forward direction (fig. 4).

Also in the case of the vertical planes the curves are influenced by the addition of reflectory planes. If for instance the experiments in the vertical plane are performed on top of a table with reflecting leaf (in the other experiments we always worked on a table with a leaf of wire gauze, which doesn't reflect the sound) then for the lower part of

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the curve the S-shape and the compression disappears completely, so that the observation comes in closer agreement with reality.

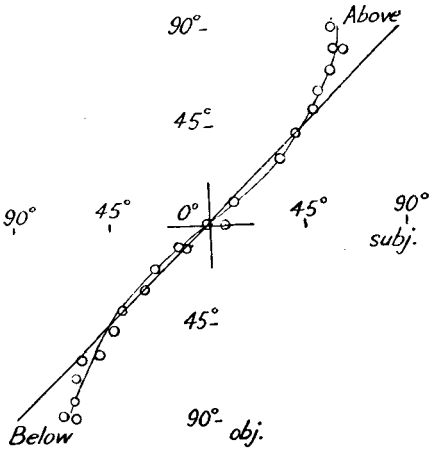


FIG. 4

Plane of investigation: vertical front plane. Source: a^3 organ pipe. Zero point straight in front of the test person in the horizontal plane through the aural axis. Further data as in Fig. 1.

COMPRESSION

Elimination of the Influence of the Auricles

As mentioned before we have tried to influence the process of directional hearing by eliminating the auricles. In the first place we tied them flat on to the head with a tight bandage with a sufficiently

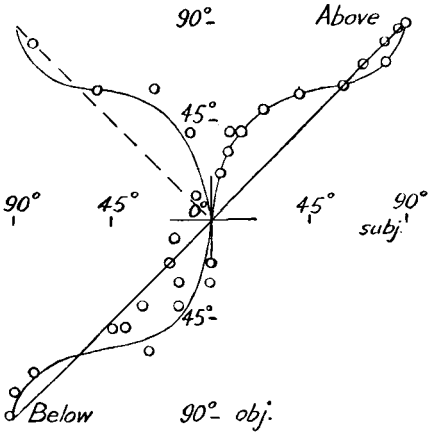


FIG. 5

Plane of investigation: vertical left side plane. Source: Galton flute. Glass tubes in the ears. Further data as in Fig. 3.

STRONG DOUBLE S-SHAPE AND REFLECTION ESPECIALLY FROM BELOW TOWARDS ABOVE

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large hole for the external auditory canal and the concha auris. Furthermore with the same purpose we placed little glass tubes of about 6 cm. long and the same diameter as the auditory canal into the latter*. The effect of the two methods was essentially the same but somewhat more pronounced with the latter. The result was that all spontaneous deviations of the curves became more pronounced. In this way a strong S-shape and compression of the curve (fig. 5) resulted from experiments in the vertical side plane. Also mirrored images and sometimes the formation of a virtual sound image (fig. 6) giving the suggestion of the

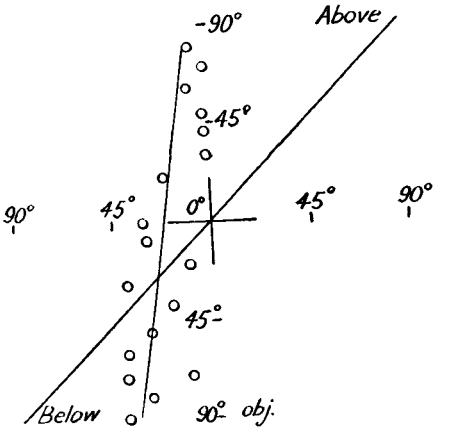


FIG. 6

Plane of investigation: vertical front plane. Source: a^3 organ pipe. Tubes in the ears. Further data as in Fig. 4.

FORMATION OF A SOUND CENTRE

tone originating within the head instead of outside, were observed. In the vertical frontal plane the localization becomes practically impossible. In the horizontal plane the effect is less strong than in the vertical planes. Usually a stronger S-shape, especially a double S-shape (fig. 7) caused by a displacement towards the centre is observed. Also the discrimination between sounds coming from behind and before us becomes extremely difficult. The auditory acuity of the test person was not decreased by the elimination of the auricles neither by tying them to the head nor by the use of the tubes in the auditory canals. Also both the capacity to understand whispering and the audiogram remained unaltered. We only observed that the resonance frequency of the ear with and without tubes differed by 200 Hz. This frequency amounted to about 1100 Hz. unaided and to about 900 Hz. with the tubes.

* This idea has been used by Gellé already in one ear.

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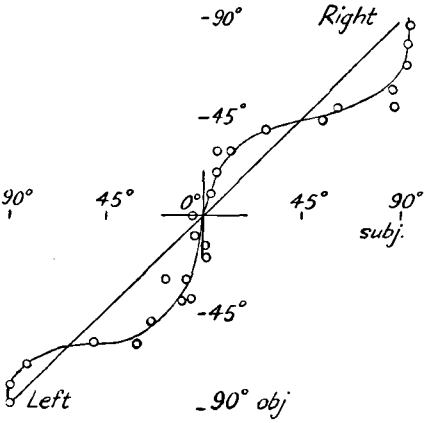


FIG. 7
Plane of investigation: horizontal. Source: e^2 organ pipe. Tubes in the ears. Further data as in Fig. 1.
DOUBLE S-SHAPE

Closing of one Auditory Canal

Finally we investigated the effect of closing one of the auditory canals by means of a piece of cotton wool soaked in paraffin wax. This caused a decrease of the intensity observed by about 15 db. somewhat dependent on the height of the tone. No influence in the frontal vertical plane could be established. In the vertical side plane a displacement

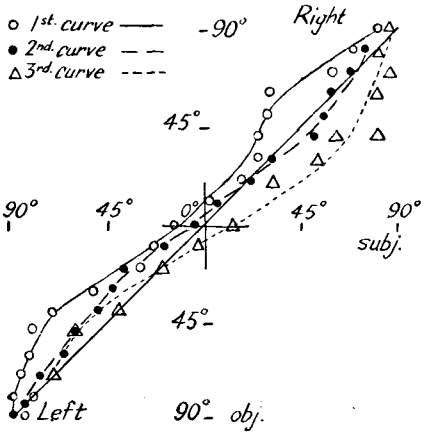


FIG. 8
Plane of investigation: horizontal front plane. Source: pure sine of 1000 Hz. Further data as in Fig. 1.
First curve: immediately after shutting off the right ear with a piece of cotton wool with paraffin wax causing an intensity loss of 17 db.; displacement towards the left.
Second curve: 2 hours later; decreasing deviation to the left.
Third curve: immediately after removal of the cotton wool; displacement towards the right.

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of the observed sound source towards the normal ear is found ; the same was observed in the horizontal plane. After several hours this deviation decreases however and is only slight after 24 hours. When after those 24 hours the cotton wool is removed from the closed ear, a displacement of the observation towards this ear takes place, which lasts only a few minutes (fig. 8) so that during the determination the deviation fades away. Finally we were able to do some determinations with persons with hardness of hearing on one side. As long as the hearing was such that the investigated sound stimulated both ears, rather good directional hearing was present. If one ear was deaf or appreciably hard of hearing, the directional hearing was bad to very bad. But even with total deafness of one ear some directional hearing remains in the vertical plane and in the horizontal plane at the side of the sound ear. Further investigations are necessary before drawing definite conclusions.

Summary of our own Experiments

Surveying our experiments it seems that few conclusions can be drawn from them regarding the nature of the process of directional hearing. We wish however to point towards a few considerations which may guide further experiments.

In the first place we could corroborate that it is easier to determine the direction of complex sounds than of a pure sine. It was not found to be true that a sound of 500 Hz. could be localized more easily than one with a higher frequency. In the vertical side plane we even found a stronger S-curve for the former kind. The localization of the 4000 Hz. sine or of the Galton whistle were certainly not worse than that of the 500 Hz. sine and the e^2 organ pipe.

We cannot explain the curious S-shape, observed almost constantly in the horizontal plane. It indicates that more accurate localization occurs in the direction of the produced aural axis and perpendicular to it than in any other direction.

The elimination of the auricles by tying them flat against the head or by placing tubes in the auditory canal makes vertical directional hearing almost impossible, whereas in the horizontal plane it also becomes more difficult. Also reflection has a strong influence on directional hearing, which should not be neglected.

A decrease of auditory acuity of one ear has not much influence on the vertical directional hearing and even total deafness of one ear leaves some sense of direction, both vertically and horizontally to the side of the sound ear. Hardness of hearing as a result of a swab of cotton wool soaked with paraffin wax has effect immediately, but after a few hours a loss of 20 db. is already practically compensated. On the other hand a displacement of the sound image towards the ear from which the paraffined cotton wool is removed after an insertion of 24 hours, fades away completely in the course of a few minutes.

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If it is true that intensity differences of the sounds at both ears are responsible for a large part of the directional hearing in the horizontal plane, it is, in any case, advisable to be aware of the fact that this is no fixed difference nor ratio, but one the interpretation of which is adapted to circumstances such as shutting off one ear. The experiments on elimination of the auricles indicate that, besides phase-, time- and intensity-differences still other factors play a part. Possibly the timbre differences owing to diffraction around the head are more important than has been hitherto believed.

No arguments could be derived from our experiments in favour of the view of van Soest (6) and Wallach (11) that by small movements of the head, the exact position of the sound source is determined on the rotational surface belonging to a given phase and intensity difference. No more than such a surface can be caused theoretically by those differences. Some data must be added to cause an exact localization of the sound source on this cone. It remains obscure from this standpoint why a pure sine is localized in the vertical direction with so much more difficulty than in the horizontal direction. The same is true for the elimination of the auricles. Moreover it is strange that a virtual sound image never gives rise to a sensation of higher or lower, but only left or right and perhaps forward and backward.

The impossibility of localizing pure sine tones, to determine the place when the influence of the auricles is eliminated, and the independence of deafening of one ear for the directional hearing in the vertical plane are all indications that here a different explanation will have to be sought and possibly also here the changes of timbre are important, owing to diffraction around the head and especially around the auricle.

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