THE LOCALISATION OF SOUND.

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THE word "localisation" as applied to sound is of psychological rather than physical origin. It deals with a sensation more than with a physical measurement. It differs from location in that it does not fix the position of a source of sound.

Stereoscopic vision does not find its counterpart in hearing, although Hartley, in America, has attempted to show that we are partly endowed with a faculty of sound-location, or what we may call "stereotic audition."

It may be stated, however, that with our unaided listening equipment we can only obtain a sense of direction. Although we may not be conscious of it, we derive our sense of direction from an "image" which is subjective, and whose direction, relative to the sagittal axis of the head, enables us to point to the source with a greater or less degree of accuracy. This image is located along the arc of a circle having the aural axis as a diameter. Sometimes the circle is larger than the head, *i.e.*, there is external localisation, and sometimes it is apparently inside the head. These characteristics are peculiar to the individual.

The head, as normally placed, is best adapted for listening in a horizontal plane. Starch has shown that localisation is most accurate in front, nearly as accurate for the back, and least accurate at the side. For all-round listening, accuracy in localisation is least for the overhead position. Thus, if the head be maintained erect, an aeroplane may pass over an angle of 20 degrees of arc, 10 on each side of the vertical, without giving the listener any clue as to its change in position.

It has always been recognised that, in normal cases, localisation occurs by virtue of some difference in stimulus received by the two ears. There are three ways in which such variation in stimulus can arise, viz., by: (1) Difference in sound intensity; (2) difference in phase of the incoming sound waves; (3) difference in time of arrival of some corresponding portions of the sound waves received by the two ears.

Dealing with these theories in order:—

(1) The theory of localisation by difference of sound intensity in the two ears was the first one to hold the field. Its principal

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advocates were Silvanus Thompson, Kessel, and Fechner. These authorities found that localisation occurred in the ear receiving sound of greater intensity.

The most authoritative pronouncement against the theory is that of Rayleigh, who showed mathematically that by treating the head as a spherical obstruction, a maximum difference of intensity of only 10 per cent. occurs round the head for a tone of frequency 256 vibrations per second, while for a tone of 128 vibrations this is reduced to about 1 per cent. It has been shown by Harvey Fletcher that the ear is incapable of appreciating intensity changes of less than 10 per cent.; hence no localisation can be possibly obtained for notes of frequency less than 256 vibrations per second. For higher-pitched notes the intensity variation is, of course, greater, and when it becomes large, the intensity theory of localisation will hold. It will be seen later that for high frequencies the phase theory breaks down.

We conclude, therefore, with Rayleigh, that localisation of sounds of high pitch is chiefly due to variations of intensity. In general, unless special precautions are taken, there are high-pitched constituents in the sound, so that localisation, if not obtained primarily by intensity difference, is certainly helped by it.

As the technique of sound measurement improves, more definite information can be obtained, and the more recent experiments of Banister have done much to clear up the situation. By the use of telephones and triode valves, Banister has built up an instrument capable of generating almost pure tones of any required frequency, and has been able to convey to the ears sounds of varying intensity while at the same time keeping them in phase. In this way he has shown, as the result of exhaustive trials with various normal observers, that no change in localisation occurs until the ratio of intensities has an average value of 2·6.

The ratio 2·6 would appear to explain the conflicting results of the various observers. When the degree of deafness does not exceed a certain amount localisation is correct.

(2) The phase theory of sound-localisation rests on a firmer experimental basis. Its chief protagonist is the late Lord Rayleigh, and it has the support of Stewart and Banister, both of whom have devised apparatus to confirm the theory.

Stewart devised an ingenious little alternator which

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generated electrical current in two telephones. When these two currents were in phase in the telephones, the observer received a fusing of the sounds and central localisation; but, if the phase of one alternating current were gradually changed, the sound image moved round the head.

When the phase-variation device is not hampered by resonance, the following phenomena are observed by an experienced subject:—

At 0° phase difference, the sound is localised as in front and external to the head.

As the phase differences increase to 90°, the sound image describes a horizontal curved path, with the image gradually nearing the head until it appears to enter the ear leading in phase.

Beyond 90° it passes through the head, passing the median plane at 180°.

Beyond that, it passes rapidly to the opposite ear till the phase difference is 270°, after which it passes out of the head to the median plane again at 360°.

Summing up all the evidence of recent observers, it appears certain that, for the lower frequencies, corresponding to tones of average conversational frequency, localisation is chiefly by phase difference. There is a wide difference of opinion between different observers as to the upper limits of frequency at which phase difference is in operation for location.

When the acoustical wave-length is short, the phase changes may pass through two or three complete cycles when moving the head, and there would be, therefore, a succession of images, so that the central localisation is indefinite. This ambiguity occurs above 800 vibrations per second, although Stewart and others place the limit at a much higher frequency.

With regard to the lower limit, it is our experience in the Army that it is extremely difficult to locate, whether by phase or intensity, the very low-pitched pure notes. The lowest notes of an aeroplane, for instance, present great difficulty, but the aeroplane sound as a whole is easy to locate, because it is so rich in high-pitched and impulsive sounds.

(3) Time-difference theory. This has been recently enunciated by Boring. The two halves of the brain, receiving nerve impulses with a certain time lag, interpret these as conditional to the forming of an "image" deviated to an extent proportional to that lag. That the ear is capable of discovering such lags was shown by Lowell Bennett in America. He

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produced clicks in two telephones placed against the ears and, by gradually reducing the intervals between clicks, was able to get them fused into one sound which the observer recognised as a definite image, and which was towards the ear receiving the first click. By progressive reduction of this time interval, Lowell Bennett was able to detect a time difference of 6·5 millionths of a second. Of all the properties of the ear as a scientific instrument, this is probably the most remarkable.

Banister has developed a theory which combines the time-difference and the phase-difference theories. He accepts Helmholtz's resonance theory and assumes that nervous impulses from the appropriate nerve-ending in the basilar membrane are transmitted along the auditory nerve, thereby registering the stimulus received. These impulses are not of the form of a continuous flow of energy, but are followed by a refractory period during which they are incapable of transmitting any further impulse. For the average sensory nerve Adrian has shown that there is a refractory period of one five-hundredth of a second.

The assumption is made that hair cells of the organ of Corti are stimulated, resulting in a displacement of the cilia embedded in the tectorial membrane, and that the impulses are generated when they are in a certain phase of their cycle.

Sharp clicks would start off the impulse along the auditory nerve, and if these clicks are imparted to the two ears at different times, that time difference will be repeated between the impulses. If the sound is continuous, the nerve impulses are supposed to be generated when the cilia suffer a certain extension. Phase difference would therefore be distinguishable, since these critical displacements would show lags equal to the phase lags.

Instruments for Sound-Location by Aural Methods.

The Army has devised instruments for sound-location of aeroplanes by listening, and binaural apparatus is employed. Two requirements are essential for sensitive and accurate instruments: (1) The sound should be magnified and isolated from surrounding disturbing sounds; (2) The base length between the ears should be artificially increased.

In the aeroplane sound-locator, magnification is effected by trumpets whose dimensions are as large as is consistent with

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portability. The sounds are led into the respective ears by stethoscopes. Base length is increased by suspending the trumpets and extending the listening tubes, so that, in the Service pattern, the trumpets are 4 feet 6 inches apart, and the effect of this is to magnify nine times the phase shift which is produced by an equal turning of the head.

The instrument so designed will give a direction, working on intensity alone, since the trumpets are directive, but accurate location can be only secured by working on phase difference. The listener must be able to appreciate the sound image subjectively produced and must experience the sense of passage over the median plane. This capacity is essential, therefore, in selecting listeners, and, in general, can be discovered directly the subject handles the locators.

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