trace any electricity whatever to this source. The problem of the source of the electricity of the atmosphere is still unsolved. Evaporation, first proposed by Volta, whose theory until now has been better supported by experiment than any other, fails to account even for a small portion of it; and no other source has been proposed which can yet be considered sufficient.

LI. *On the Function of the two Ears in the Perception of Space. By* Professor SILVANUS P. THOMPSON, *D.Sc., B.A.*

1. THE conceptions formed in our minds of the extension of space may be resolved into two parts:—(1) the conception of distance independent of direction; (2) the conception of direction independent of distance.

These conceptions are founded upon the perceptions of three separate senses, each of which, though distinct from the others, enables us to form conceptions both of linear magnitude (or distance) and of angular magnitude (or direction). These three senses are:—

(*a*) The muscular sense;
(*b*) The optical sense;
(*c*) The auditory sense.

(*a*) The *muscular* sense gives us direct perceptions of linear magnitude and of angular magnitude through the sensations produced by extending the limbs and by twisting the frame and head.

(*b*) The *optical* sense gives us perceptions of angular direction of two kinds:—the first of them depending upon the optical formation of images of external objects upon the differentiated nerve-structures of the retina of the eye; the second of them being partly optical, partly muscular, and derived from the sense of muscular effort required to move the eye-balls, or the whole head, into the position in which light from an object situated in any given direction shall be most easily observed. The optical perception of distance is of three kinds—one kind being indirect and associative, the other two muscular. The *first* of these depends upon the possession of two eyes, giving, in consequence, two retinal pictures with slight differences, which we gradually learn to associate with varying conditions of distance. The *second*, and principal, of them depends also upon the possession of two eyes, the greater or lesser amount of muscular effort required to converge their optic axes in viewing an object affording a basis for a mental estimate of

* Communicated by the Author, having been read before Section D of the British Association at York, September 1881.

distance. The *third* of them does not depend upon the possession of two eyes, or upon "binocular parallax," but consists in the perception by the muscular sense of the amount of effort which the ciliary muscle must exert to focus the eye for rays proceeding from an object at a given distance. The author has elsewhere * shown how this last mode of perception is complicated by the question of the colour of the rays in consequence of the imperfect achromatization of the eye. To these three a fourth, and purely associative, kind of perception of distance must be added, in the apparent magnitude of objects of known size. Of these modes of perception, the two depending on binocular parallax are of greatest importance; without them our optical conceptions of solidity and distance would be extremely imperfect. The theory of binocular vision was practically complete when the invention of the stereoscope, and of its *reductio ad absurdum* the pseudoscope, proved the general correctness of Wheatstone's views, though several corollaries to the theory have since been elaborated by younger workers.

(*c*) The *auditory* sense may in like manner afford us perceptions of linear and of angular magnitude—that is to say, of distance and of direction. But the theory of the acqustical perception of space is strangely incomplete. Just as the possession of two eyes gives us by binocular parallax the most important of the optical means of perception of space, so the possession of two ears is found, from the researches of Mach, Luca, Steinhauser, Graham Bell, and of the present writer, to give us, by binaural parallax, important means for receiving acoustical perceptions of space. Besides these binaural perceptions, it is undeniable that imperfect monaural perceptions of space exist. These will be noticed in passing.

2. Any comparison of the *ear* and *eye* in respect of their power of affording perceptions of space would be incomplete if three points of essential difference in the arrangements of these organs were not adverted to:—

(i) The ear has no lens, and nothing equivalent to a lens by which a sound-wave proceeding in any given direction could be focussed on the receptive mechanism. The pinna or auricle of the ear and its auditory meatus do not even serve, as a hollow parabolic reflector might serve for light, to focus rays coming in different directions on different points of the receptive membrane.

(ii) The receptive nerve-structure of the ear is differentiated in a wholly different manner from that of the eye, so that its different parts are not sensitive to different *directions* in the

* Phil. Mag. July 1877, [5] vol. iv. p. 48.

movement of acoustic waves, but only to their difference in *frequency*.

(iii) The ears cannot be turned toward different directions as the eyes can be, independently of the movements of the head, at least in man. There seems no reason, however, to doubt that the faculty of moving the pinnæ of the ears is useful to animals in their perception of the direction of a sound. It is a matter of common knowledge that horses, asses, cats, and dogs do thus use their pinnæ in ascertaining the direction of a sound. In these cases, however, it is doubtful whether there is any muscular sense of convergence to give (as with the eye) a perception of distance.

3. There are four physical characteristics of waves of sound by which one sound is discriminated from another, viz.:—

(i) *Intensity*, or loudness, depending upon extent or energy of the vibratory motions.

(ii) *Pitch*, or frequency, depending upon the rapidity of the vibratory motions.

(iii) *Phase* of the vibratory motions, as to whether moving backward or forward or at any other state.

(iv) *Quality*, or timbre, depending upon the degree of complexity of the vibratory motion.

The third of these physical characteristics is one for which the single ear possesses no direct means of perception. The author of this paper discovered in 1877 *, however, that in binaural audition a perception of difference of phase did exist; and the same discovery was made independently in the succeeding December by Prof. Graham Bell and Sir William Thomson. The existing theories of the acoustic perception of space, which will now be examined, are founded upon the perceptions of these four physical characteristics.

4. *Theories of* Steinhauser *and of* Graham Bell.—A very complete and careful theory of binaural audition was published in 1877 by Prof. Anton Steinhauser †, who worked out on geometrical principles the laws which determine the *relative intensity* with which a sound will reach the two ears when starting from any given point of space. The intensities are equal in the two ears when the source of sound is in the median plane, and is a maximum when in front, a minimum when behind the head, since the ears are set angularly (so as to catch sounds from the front of the head) in planes which determine, according to Steinhauser, the conditions of best hearing. The formula deduced by Steinhauser is the follow-

* Rep. Brit. Assoc. 1877, p. 37; Phil. Mag. [5] vol. iv. Oct. 1877, p. 274.

† Vienna, 1877; Phil. Mag. [5] vol. vii. pp. 181, 261.

ing:—Let β be the angle between the plane of the ear and the line of sight, and α the angle which the line of sight makes with the direction of the sound; and let i_1 and i_2 represent the relative intensity with which the sound is heard in the two ears; then

$$\tan\alpha : \tan\beta :: i_1 - i_2 : i_1 + i_2.$$

The operation, therefore, of finding the direction of a sound —say a lark singing high up in the air—will, according to Steinhauser, be as follows:—First, the head is rotated on its axis horizontally until the sound is equally loud in both ears; then the head is moved up and down until a maximum of loudness is discovered, when the lark will be found in the line of sight. Steinhauser's theory, it will be noted, takes into account no differences of phase, pitch, or quality, but of intensity only; and it fails, as will be seen, to account for the fact that we have, *without moving the head at all*, a very fair perception of the direction of sounds. It also presupposes (what the experiments of Crum Brown and M'Kendrick have pretty definitely shown to exist) that we possess a rotation-sense, a means of perception of angular movement in horizontal and meridional planes. Steinhauser devised an instrument, which he named the *homophone*, wherewith to test his theory. It consisted of a system of wooden tubes for bringing to the ears the sounds of two organ-pipes tuned to unison, whose respective intensities could be regulated by stopcocks. It was held by its inventor to confirm his theory.

A similar theory has been implicitly adopted by Prof. Graham Bell, in the paper on Experiments relating to Binaural Audition which he read before the American Association for the Advancement of Science in 1879 *. Graham Bell investigated the matter with telephones connected to the ears, with some curious and valuable results. He also experimented on the degree of accuracy with which the ear can determine the direction of a sound, and found it to be most accurately defined for those sounds the direction of which approximates to the axial line of the ears.

5. *Theories of* A. M. Mayer *and* (*provisionally*) *of* S. P. Thompson.—A modification of the preceding theory was provisionally adopted by the present writer in the earlier part of his researches. He had discovered that when two sounds agreeing in every respect, save in phase, are led to the ears, a singular phenomenon occurs, complete difference of phase producing an acoustical illusion as if the sound were localized in the back of the skull. He therefore suggested that differ-

* American Journal of Otology, July 1880, p. 169.

ence of phase, being thus recognizable, might assist the observer in finding the true direction of a sound; for when his gaze was directed in the precise direction, not only would the relative intensities be equal, but the phase would be identical, and the sensation would be free from complication with the illusion.

Prof. Alfred M. Mayer of the Stevens Institute, in the course of his acoustic researches, suggested an instrument which he called the *topophone*, the object of which is to ascertain the direction of a source of sound, and which depends upon differences of phase and of intensity. An experiment of Zoch (see Radau, *Die Lehre vom Schall*, p. 246) for comparing the relative phases of two simple unison-tones by means of König's manometric flames, suggested to Mayer an instrument composed of two resonators fixed at the ends of a T-shaped frame, and connected with manometric flames, whose objective vibrations, as seen in a rotating mirror, would be synchronous when the phases and intensities of the sound-waves received in the two resonators were alike, or when the cross-arm on which they were fixed stood at right angles to the direction of the sound. In another form of the instrument, the frame carrying the resonators was fixed by a kind of yoke to the shoulders, the resonators being respectively connected by tubes to the two ears. Comparatively small angular movements of the head would then produce considerable differences of *phase*, rendering the perception of direction more narrowly accurate.

6. *Theories of* Mach *and of* Lord Rayleigh.—Prof. Mach, of Prague, advanced the theory (*Archiv für Ohrenheilkunde*, 1874) that the perception of direction of sound arose from the operation of the pinnæ of the ears as resonators for the higher tones to be found in the compound sounds to which the ear is usually accustomed; their action as resonators should be more or less effective according to the position of the pinnæ with respect to the direction of the sound-waves; and by thus reinforcing in different positions with unequal intensity, some one or more of the higher tones of a compound sound should affect the *quality* or timbre of the perceived sound, producing a difference between the sounds heard in the two ears in all positions, save when the source of sound lay in the median plane of the head. There should also, according to this theory, be a difference in the quality of the perceived sound (owing to the dissymmetry of the upper and lower parts of the pinna) for sounds in the median plane according as they were above, below, or in the line of sight. It will be convenient to consider along with the theory of Mach the somewhat similar theory of Lord Rayleigh*, propounded in 1876 before the

* Trans. Mus. Assoc. 1876.

Musical Association. Lord Rayleigh pointed out that, as the size of the head bears a finite proportion to the size of sound-waves, there will be no sharp shadows of sounds occurring at the opposite side of the head to that at which a sound arrives, but that *diffraction* of the sound-waves will take place, which, in the case of complex sounds, will produce the result that the partial tones of different pitch will arrive at the side of the head opposite to that nearest the source of sound with very different intensities. Thus, without making any assumption as to the functions of the pinnæ as resonators, Lord Rayleigh's theory agrees with that of Mach in attributing the acoustic perception of direction to differences of *quality* or timbre between the two ears, the brain drawing, from the slight differences of the tones received in the two ears, an unconscious judgment based on empirical observation.

7. One other theory only will be mentioned, and this only to be at once dismissed. It is the theory advanced by Küpper *, that sound-waves proceeding in different directions affect different parts of the tympanum, and so give rise to different sensations. This is physically untenable, because the tympanum is not the true receptive organ with differentiated nerve-structures, but only a part of a mechanical device by which the alternating compressions and rarefactions taking place at the bottom of the tube of the ear are conveyed to the true receptive organ in the labyrinth of the internal ear. It is also untenable because, as Mach and Fischer have shown, the outer ear cannot act as a true reflector except for waves whose length is a small fraction of its own dimensions, which is only true for sounds of such excessive shrillness as to be out of the range of ordinary sounds. [The shrillest sound audible in human ears is of wave-length 0·4 of an inch.] It is, finally, untenable because, in fact, nothing is more difficult than to tell the direction of sounds whose source is in the median plane of the head—front, back, zenith, and nadir being usually undistinguishable except for very well-known sounds.

8. In order to test the rival theories of binaural hearing, the author of this paper devised a little instrument, described before the British Association (Section A) in 1879 under the name of the *pseudophone* †, which is for the ears what Wheatstone's pseudoscope was for the eyes, an instrument for verifying the laws of perception by means of the illusions which it produces. The *pseudophone* consists merely of a pair of adjustable flaps or reflectors which can be fitted to the ears, and which can be set at any desired angle to catch sounds

* *Archiv für Ohrenheilkunde*, n. F., Bd. ii. part 3, p. 158.

† Phil. Mag. [5.] vol. viii. 1879, p. 385.

from back, front, above, or below. By altering the position of the flaps, we alter the relative intensities of the two sounds as received in the ears; and this can be done without the blindfolded observer knowing how the flaps are set. If, for example, the flaps are set to catch sounds from behind, the observer will imagine that he is looking in the direction of the sound when he is looking in precisely the reverse direction. But when the *simple tones* of tuning-forks are used, the instrument fails to gives satisfactory illusions, except for very shrill tones, when the experiments are made out of doors.

9. The following criticisms on the rival theories and on some of the results of mathematical and experimental deductions therefrom will now be in place.

(*a*) All the theories assume that we have a rotation-sense—that is to say, that when we turn round to face a sound, we are conscious how much (in angular measurement) we have turned round. Lord Rayleigh, in his experiments, kept the head still, and estimated the angular direction of the sound without turning the head. In this case association with previous perceptions of rotational movement must, however, be admitted as entering into the mental process of judging of angular position.

(*b*) The theory of Steinhauser leads to the mathematical deduction that perception of direction is the most exact for sounds situated in the *plane of best hearing*, or in the median plane and in front of the head. The experiments of Graham Bell, on the other hand, as well as those of Mach and of Lord Rayleigh, are conclusive that the perception of "the direction of a sound is more accurately defined as it approximates to the axial line of the ears."

(*c*) Steinhauser's theory and his fundamental formula given above in § 4 assume that the ratio between the tangents of the angles will be the same in our perception as the ratio between the angles themselves. This is only true when both are small, and when therefore the source of sound is nearly in the median plane. Unfortunately for the theory, for very small angles the perception ceases to be accurate, especially for small angles near the median plane.

(*d*) Steinhauser's theory assumes the pinnæ to act as reflectors and funnels; he further assumes the magnitude of the "effective surface" to be equal for sounds coming at all angles, which is by no means proven or even probable.

(*e*) It is a mathematical consequence of Steinhauser's theory, that if the plane of the effective surface of the pinna makes an angle of less than 30° with the line of sight, a sound will be heard louder when opposite one ear than when placed at an equal distance in front of the head. With most people this angle is less; but most people, at any rate, prefer to face the source of sound when listening.

(*f*) It may be deduced from Steinhauser's theory that the perception of direction should be more accurately defined in those persons for whom the angle between the effective plane of the pinna and the line of sight is as small as possible. If this be so, persons whose ear-flaps stand off from their heads at a considerable angle should be bad judges of the direction of sounds, which is not, in general, the case. The behaviour of animals in bringing forward the openings of the pinnæ when listening intently to a sound is contrary to this point. If the deduction were true, women should be better judges of the direction of sounds than men, as their pinnæ usually are less prominent. In the experiments of Graham Bell with telephone-receivers when they were set at an angle with one another, he was able to perceive the direction of sounds more accurately than when the receivers were set parallel, the difference between back and front being thus capable of discrimination; but he does not state whether this discrimination arose merely from difference in relative intensity or from difference of quality.

(*g*) If the theory of Steinhauser is true, the perception of direction should be more accurate for sounds when their source is far away than when it is near the head. If the theory of Lord Rayleigh and of Mach is true, the perception of direction should be more accurate for sounds whose source is nearer the head. The latter is shown by experiment to be true for all kinds of sounds.

(*h*) The theory of Lord Rayleigh is supported by the experimental fact that the quality of sounds does, as a matter of fact, differ when they are heard in different directions. Compare, for example, the sound of a musically ticking clock placed in front of the head with the sound of the same clock when the head is turned in the opposite direction. To the writer the tick of a watch always sounds deeper in pitch when held in front of the head than when held opposite either ear, in each case at equal distances of about one foot away.

(*i*) The theory of Lord Rayleigh also derives support from the following observation. To analyze a compound sound by ear, so as to say what partial tones are present, requires considerable practice, and is even then not easy. But the presence or absence of partial tones is rendered much easier of detection if the head be turned about, so that their various degrees of intensity as affected by diffraction or by phase-difference may bring one or other into prominence.

(*j*) The theories of Mach and Lord Rayleigh agree with that of Steinhauser in one respect. They assign, it is true, the perception of direction of a sound to the effect of resonance or of diffraction in partially resolving a compound tone; but they make the perception of this splitting-up of the sound to depend upon the *unequal intensity* with which the resolved sounds are received in the two ears.

(*k*) The experiments of Lord Rayleigh show that our perception of direction is much more accurate for compound sounds than for simple tones.

(*l*) The experiments of the writer with the pseudophone show that the acoustic illusions are produced much the most satisfactorily when shrill sounds, such as the sound of a whistle or the click of a metronome, are employed.

(*m*) Experiments made with very low tones show that for these the sense of direction is extremely inaccurate. In this case the extreme effect of diffraction would cause the sound to be heard almost equally loudly by both ears in all positions.

10. It would therefore appear that Steinhauser's theory may be true for shrill and simple tones, and therefore true for the particular case of the lark. But for baser tones and for compound tones it cannot be regarded as true. For these the resolution-theories of Mach and Lord Rayleigh are much more nearly in accord with the facts of observation; though it probably yet remains to be determined whether the resolution of compound tones supposed in those theories be due, as Lord Rayleigh assumes, to diffraction round the head, or, as Mach assumes, to the pinna and its convolutions acting as resonating-cavities to reinforce certain of the partial tones of the compound sound. The former is the more probable in the opinion of the present writer; but it is not without its difficulties.

If in binaural hearing the direction of sound were to be estimated only by the process of moving the head until the line of sight coincided with that of the sound, then Steinhauser's theory accounts best for the facts.

If, however, the direction be estimated while the head is held immovable, then the resolution theories are certainly the more satisfactory.

In view of the fact (as apparently shown by Graham Bell's experiments) that even in *monaural audition* there is a fair perception of the direction of sound, Steinhauser's theory utterly fails to have any significance; while the theories of Mach and of Lord Rayleigh are amply sufficient for the facts.

11. The writer therefore propounds the following theory, which he believes to cover all the facts observed up to the present time.

Judgments as to the direction of sounds are based, in general, upon the sensations of different intensity in the two ears; but the perceived difference of intensity upon which a judgment is based is not usually the difference in intensity of the lowest or fundamental tone of the compound sound (or "clang"), but upon the difference in intensity of the individual tone or tones of the clang for which the intensity-difference has the greatest effective result on the quality of the sound.

It must be admitted that the acoustical perception of direction is, after all, not intuitive, but associative, just as the optical perception of direction is. The ear has been trained from childhood to associate certain differences in the quality of sounds (arising from differences in the relative intensities of some of the partial tones that may be present) with definite directions; and, relying on these associated experiences, judgments are drawn concerning sensations of sound whose direction is otherwise unknown. For sounds that are familiar a difference of quality as heard *in one ear* will at once suggest a direction. It is completely open to doubt whether a pure simple tone heard in one ear could suggest any direction at all.

12. *Acoustical Perception of Distance.*—There remains for discussion the acoustical perception of distance.

In the case of known sounds we doubtless judge chiefly of their distance by their relative loudness, the intensity decreasing inversely as the square of the distance. The analogous fact in optics is the perception of distance by the apparent magnitude of objects familiar to the sight and of known size.

It might be possible indirectly, in the case of short distances, to judge of distance by "acoustic parallax"—that is to say, by the difference in the direction of the sound as perceived in the two ears. The quality of a compound sound also differs slightly with distance (independently of direction); and from this fact a judgment might be drawn. It must be held extremely doubtful, however, whether any such judgments are actually made.

13. *Conclusion.*—The foregoing arguments and deductions have been based upon observations made, so far as the author is aware, exclusively by and upon persons possessed of normal powers of hearing. Nevertheless the subject is of such a nature that its more obscure points would doubtless be greatly

elucidated by observations made by and upon persons whose hearing-power is abnormal. The author has had no opportunities of making such observations. He has heard of one case of interest—that of a gentleman stone-deaf of one ear from infancy, and in whom the acoustic perception of direction was almost wholly wanting. Not only are experiments greatly wanted upon semi-deaf persons, but also upon blind persons, who usually have the acoustic perception of direction abnormally acute. It would be still more desirable to have observations made on a blind person deaf of one ear.

It is also greatly to be desired that further experiments should be made to determine the exact function of the pinnæ and of their complicated forms. The convolutions of the pinnæ differ markedly in different persons, and such differences must have *some* effect on the perception of sound. The suggestion of Mach, that the convolutions have no direct acoustic function in man, but that they represent the corresponding structures which in animals serve to direct the opening of the pinnæ or to prevent them from being turned inside out, is probably true, and is in conformity with the doctrine of descent, which accounts for many other inherited but functionless appendages. Yet, if true, this does not affect the truth of the statement that the convolutions, though destitute of direct function, must still exercise some effect on the perception of sound. In particular, it may be remarked that the outer cartilaginous rim of the ear curves forward at the upper part of the pinna, as if to catch sounds proceeding from below the observer and in front of him. Is it possible that this arises by natural selection from the fact that, on level ground, sounds reach us more intensely from below, by reflexion from the ground? And is it not also connected with the fact that persons who are partially deaf in both ears habitually throw the head a little backward, so as to raise their line of sight above the direction of the sound of the speaker's voice?

Whether the varieties of form of the pinnæ eventually prove to be of little or no importance in the question, there is an ample field for observation for anatomists and physiologists in the problems of the acoustical perception of space; and it is hoped that research in this department of physiological physics will be facilitated by the attempt now made to lay down the physical and experimental bearings of the question.