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ON A MODIFICATION OF THE HELMHOLTZ THEORY OF HEARING.[1] By Albert A. Gray, M.D., F.R.S.E.

When engaged in examining, under the microscope, a section of the cochlea of the white mouse, the writer was struck by an anatomical fact which appeared to him to be of considerable importance in regard to the question as to the way in which this organ performs its function.

The fact referred to is simply this, that the ligamentum spirale increases in size and becomes more distinctly fibrous as it passes from the apex of the cochlea to the base. The transition, though gradual, is a very pronounced one in both respects, and it is to be added that the larger and more fibrous it becomes, it takes up the usual microscopic stains, particularly the extra nuclear ones, with increasing avidity. The accompanying figure shows these facts plainly enough. It represents a section of the human cochlea.

On observing this fact, sections of the cochlea of other animals were examined, and the same fact was found to be true in all cases. The animals were the guinea-pig, rat, rabbit, kitten, calf, and the human subject, and in the last it was most pronounced. We may therefore assume that it is true of all mammals.

Now whether this has been described by anatomists before or not, it has not had that attention at the hands of the physiologist which it deserves, for if we take it in relationship to the other well-known facts concerning the basilar membrane and its appendages, it is remarkable. Thus it is well known, and has often been cited in physiological discussions, that the basilar membrane itself gradually diminishes in breadth from apex to base, while the rods of Corti, the hair-cells, and the hairs themselves, all become smaller.

It was this diminution in size of the structures connected with Corti's organ which Helmholtz urged strongly in support of

[1] Read at a meeting of the British Association for the Advancement of Science, held at Dover, September 1899.

his well-known theory that the analysis of sound takes place in the cochlea. He looked upon the basilar membrane as being made up of many strings, those at the apex being comparatively long, while those at the base were short; the former, therefore, were supposed to resonate in sympathy with deep notes, and the further down the basilar membrane we go, the shorter do the strings become, and, therefore, resonate in sympathy with higher notes. Each string, therefore, according to Helmholtz, vibrates

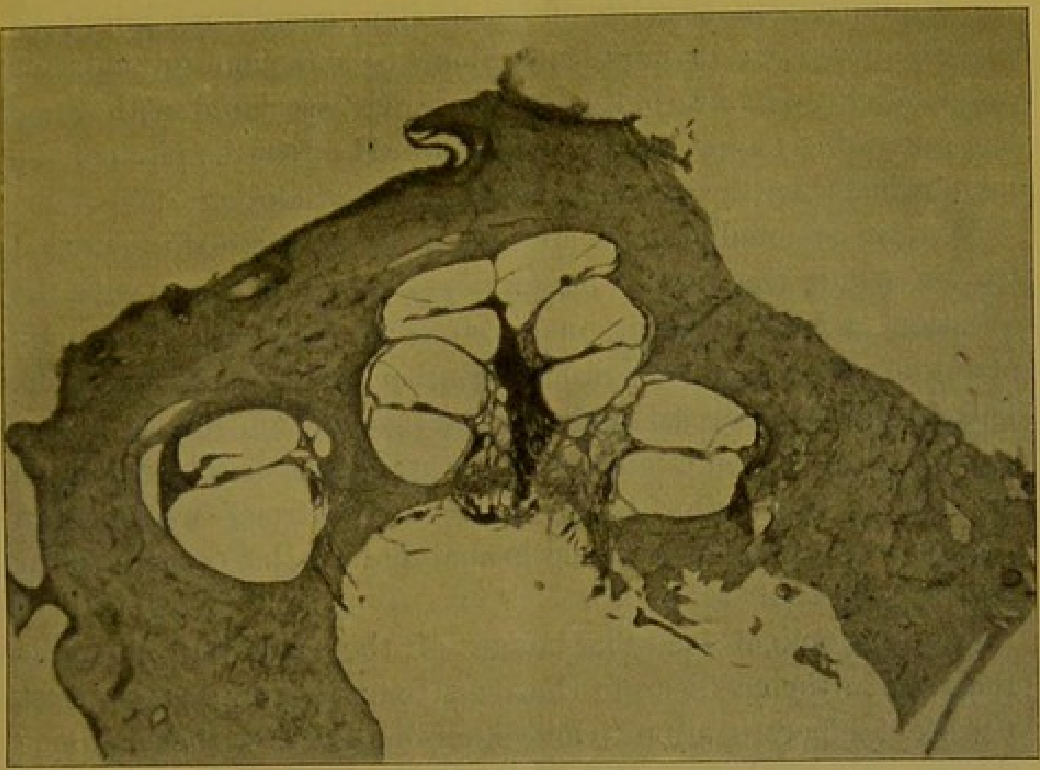

Fig. 1.—In preparing the section of which this is a photograph, the lowest portion of the basilar membrane became dislocated upwards and laterally; hence it appears twice in the lowest whorl to the left.

in sympathy with a particular note. Keeping this in view, it will be of interest to see how the fact above referred to affects the correctness of this theory.

In the first place, it is clear that since the ligamentum spirale consists either of unstriped muscular fibre, or, more probably, of fibrous connective tissue, it must produce tension on the basilar membrane. And further, since, as above described, it increases greatly in size from the apex of the cochlea to the base, then the tension exerted by it on the basilar membrane must increase to a corresponding extent. Now, if we look upon the basilar membrane as a series of strings, as Helmholtz did, then these strings must be under gradually increasing tension the further towards the base of the cochlea we go, and this being so, their vibration-frequency must increase correspondingly. The fact of the increasing size and strength of the ligamentum spirale downward, therefore, strengthens immensely the view that sound is analysed into its simple harmonic constituents by the cochlea. The change in size of the structures of the organ of Corti, and the diminution in breadth of the basilar membrane, might be mere coincidences, or might not alone be sufficient grounds for supporting this view, but when we have associated with these the remaining factor, tension, which would affect the pitch of the membrane, then the evidence appears overwhelming.

It must be noted that we are not as yet dealing with the exact way in which the cochlea may analyse sound, but only with the question as to whether it analyses sound at all, as Helmholtz maintained, or not, as Voltolini, Rutherford, and Waller held. This fact of the increasing size of the ligamentum spirale downward, which has not claimed the attention of physiologists, appears to the writer to be exceedingly strong evidence in favour of the view that sound is analysed in the cochlea so far as it is ever analysed at all.

The anatomical facts in favour of the view that sound is analysed in the cochlea are thus so strong, that it seems almost a work of supererogation to add other objections to the telephone theory, as it has been called, of Rutherford and Voltolini. This theory, shortly stated, is, that the basilar membrane vibrates as a whole to every note, and the nerve fibres transmit to the brain stimuli of a frequency the same as the vibrations of the notes.

In addition to the well-known objections to this theory, the present writer has to add another, which is founded upon pathological evidence. He had the opportunity of seeing a post-mortem examination upon the body of a young man whom he had examined during life for deafness and loud singing noises in the ear. At the post-mortem no disease of either the middle ear or labyrinth was found, but in the substance of the medulla, and involving the roots of the auditory nerve, was a small tumour. One or two other cases of a similar description have been recorded (Siebenmann, "Ueber d. central. Hörbahn," etc., *Zeitsch. f. Ohrenh.* Bd. xxix., s. 78).

Now it is surely impossible to conceive of a slowly-growing tumour stimulating the nerve fibres at a given rate per second, and yet if the telephone-theory were correct, it would require such a condition of affairs to produce the sensation of a singing noise. On the other hand, such a case offers no objection to the view that sound is analysed in the cochlea, for these theories only require that if the nerve fibres be stimulated in any way the sensation of sound will be produced in the mind.

There are other objections to the telephone-theory of the cochlea, but they have been published elsewhere. (Vide *Text-book of Physiology*, vol. ii., edited by Schäfer. Chapter on "Hearing," by M'Kendrick and Gray. In course of publication.)

It only remains to add that an objection to the view that sound is analysed in the cochlea, has been made in reference to the differential tones. These tones, according to those who put forward this objection, cannot set resonators in vibration, and must therefore be generated in the mind of the listener, which, if it were true, would be fatal to the theory that sound is analysed in the cochlea by sympathetic resonance. Recent investigation, however, by Forsyth and Sowter (*Proc. Roy. Soc. Lond.*, lxxxiii., 1898, p. 396), has shown that differential tones can be resonated if the resonator is sufficiently accurate. Furthermore, it has been pointed out that differential tones may be generated in the middle ear—Helmholtz (*Tonempf*, 3rd edit., trans. by Ellis, p. 237), Preyer (Wiedemann's *Annal.*, xxxviii., s. 131), and others; and this would fully account for the fact that it is admittedly difficult, though not impossible, to resonate differential tones.

There is, therefore, no satisfactory objection to the view that sound is analysed in the cochlea, and we have seen that both on anatomical and pathological grounds there is very good evidence in favour of this view. Other reasons in support of it will be found in Schäfer's *Text-book of Physiology*, vol. ii., *loc. cit.*

Having thus cleared the ground, we may now go on to discuss the means by which sound is analysed in the cochlea.

The first subject that comes under notice is the theory of Helmholtz. This theory is very simple, and is well known.

Helmholtz looked upon each transverse fibre of the basilar membrane to be tuned to a particular tone and no other, so that when that tone, either by itself or in conjunction with other tones, is transmitted to the fluid in the labyrinth, the fibre (possibly also one or two adjacent ones) is set in sympathetic vibration. The nerve-fibre which is in contact with the hair-cell corresponding to that fibre, will thus be stimulated, and, the stimulus being carried to the brain, we are conscious of the existence of that particular tone. When the tone is a compound one, therefore, those fibres of the basilar membrane which are in sympathy with the several simple tones of which the compound tone is composed, will be set in vibration, and we become conscious of the co-existence of several simple tones of different pitch.

This theory in some respects suits the facts of the case very well. It is in keeping with the gradual decrease which the fibres of the basilar membrane undergo in length from apex to base. It is, further, in keeping with the increase in size and strength of the ligamentum spirale downwards, as described at the beginning of this paper, though unknown when Helmholtz put forth his theory. For obviously, as the fibres become shortened and more tense towards the base of the cochlea, their vibration-frequency becomes increased. Helmholtz's theory also explains the fact, which has been discovered by pathological and clinical examination, that when the lower turns of the cochlea are affected by disease the hearing for the higher musical notes is lost.

To the acceptance of Helmholtz's theory as it stands there appears to the writer to be some very serious objections; indeed, unless they are explained these are fatal to the theory. Amongst other objections which have occurred to the writer are these:—The existence of noise as distinguished from musical sounds; the fact that the ear is, under certain circumstances, able to appreciate difference of phase.

Helmholtz appears to have been, to a certain extent at least, aware of these difficulties, for he tried to explain the first in a way which we now know to be inadmissible, and he denied the truth of the second altogether, whereas we know now that the ear does appreciate phase under certain circumstances.

Taking up the first difficulty, the existence of noise as distinguished from musical sounds.

Helmholtz first of all makes the assumption that a sound is noisy in character on account of the irregularity of the wave. But upon examination this assumption is found not to be warranted, as the writer has found out by the following experiment.

Four tuning-forks (two ut_4, si_3, and $si_3\flat$) were taken; these forks were weighted so as to form a series, with intervals of about twelve to twenty vibrations per second, so that when any two consecutive forks were sounded they gave twelve to twenty beats per second. When all were sounded together with the requisite intensity a *noise* was produced, with only a very slight trace of musical element in it. In this case, of course, the wave form would be very irregular. The next step was to take four forks each one octave above the other, and mistune them in the same way as the first set were mistuned. The forks selected were:—ut_2 (128 v.d.), ut_3 (256 v.d.), ut_4 (572 v.d.), ut_5 (1024 v.d.), and each was mistuned so as to give approximately twelve beats with the preceding one; thus the second fork gave twelve beats with the first, the third gave twelve beats with the second, and the fourth gave twelve beats with the third. When these were all bowed together the resulting sound was not merely a noise, but a musical sound, though, of course, a somewhat discordant one. There was a slight noisy element present, but this was probably due to the upper partials of one fork having a pitch nearly the same as the upper partials of some of the others, and thus producing a noise in exactly the same way as in the preceding experiment. Experiments of this kind with tuning-forks are, of course, rough, on account of the difficulty of getting the requisite intensities and also of getting the proper intervals. A series of suitable organ pipes would, no doubt, give more satisfactory results.

Now, in the second experiment, the vibrations or the wave-forms representing them are just as irregular as in the first one; in fact, they are probably more so, but the resulting sound was much more musical in the second experiment. It appears, therefore, that the noisy character of a sound does not depend only upon irregularity of vibrations, as Helmholtz assumed.

To proceed further. After assuming that noise was due to irregularity of the vibrations, Helmholtz suggested that the portions of the labyrinth which were concerned in transforming these vibrations into nerve-stimuli were the crista and macula acustica. At the time Helmholtz wrote, the suggestion, although a matter of conjecture, was perfectly legitimate, but in the light of subsequent research by Crum Brown, Mach, Goltz, Ewald, and many others, physiologists have come to the almost unanimous opinion that these structures are not concerned in the perception of sound.

We are therefore driven to the conclusion that noises as well as musical sounds are perceived by means of the cochlea.

There is yet another objection to Helmholtz's theory. Noise has pitch. It is not meant that the exact pitch, in the musical sense of the term, can be given, but it is a matter of common observation that noises have pitch relative to one another. Thus, the ticks of different watches have different pitches. Irregular shaped blocks of wood or iron, or indeed any substance, give noises of different pitch according to their size, shape, and texture, although the sounds given forth are clearly noises and not musical sounds. If, then, the cochlea enables us to judge of the pitch of a musical sound, it is but reasonable to suppose that it also enables us, though more roughly, to judge the pitch of a noise, especially when we remember that there is no sharp line of division between noises and musical sounds.

Further evidence of the relationship between noise and pitch is furnished by the following experiment. A set of four forks at close intervals were taken and mistuned, as in the previous experiment, so that the second gave about twelve beats with the first, the third gave about twelve beats with the second, and the fourth gave about twelve beats with the third. Then another set of higher forks, also at close intervals, were mistuned in exactly the same way. When all the first set of forks were bowed a noise resulted with hardly any musical element in it. So also when the second set were bowed the result was only a noise. But in the second case the noise was clearly of a higher pitch than the first.

From these experiments the natural deduction is that noises have pitch relative to one another, and that the sound vibrations affect the nerve-terminations in the cochlea in some way unexplained by the theory of Helmholtz. For if the noise were analysed into its constituents by the transverse fibres of the basilar membrane, why is it that we can obtain little or no musical element from the sound however much we concentrate our attention, and still less can we analyse the sound? In this respect noise differs from a discord. A discord may be, and often is, clearly a musical sound.

As regards the perception of the difference of phase of a sound by the ear the question is a somewhat complicated one.

Of course the single ear[1] can distinguish no difference between the two phases of a pure simple tone. Neither can the ear distinguish the difference in phase in a complete harmony, and from experiments which I have carried out I find that the single ear perceives no difference in phase in a mistuned unison. But Lord Kelvin (*Proc. Roy. Soc. Edin.*, vol. ix. p. 602) showed that in the case of imperfect harmonies other than a unison, the ear did notice a difference according to the phase. The difference was for the most part more noticeable in imperfect ternaries than binaries.

Helmholtz's explanation of this is that the ear does not perceive a difference in the phase, but that some upper partials of the two notes were beating together. To this, however, there is the objection that the sounds were produced by tuning-forks, the purest of all tones.

There is yet one other objection which the writer would like to make against the theory of Helmholtz, and which he deduces from the following experiment:—Two ut_3 tuning-forks were chosen, and one was mistuned to give four beats per second with the other. When the forks were sounded separately the difference in pitch was clearly noticeable. On sounding the two together the beats were of course heard, but there was no analysis of the sound into its two constituents. That is to say, there was heard only one note, subjected of course to the interruptions of the silences.

Now, if the ear really analysed the sound then we should have been able to distinguish the difference in pitch of the two

[1] The power of the two ears, separately, to perceive differences of phase as described by Prof. S. P. Thompson, does not come into consideration in this matter.

generating notes even better than when they are sounded separately, for we should have the opportunity of simultaneous comparison as in the case of two approximate shades of colour seen by the eye. Of course the difficulty cannot depend upon the want of delicacy of the ear, because, as we saw, it can perceive the difference clearly enough if the forks are sounded separately. If, however, beats are produced on an imperfect harmony other than a unison, then the beats are heard, and the difference of pitch of the two generating notes is also perceived clearly enough.

In view of these difficulties in the way of accepting Helmholtz's theory as it stands, the writer ventures to put forward the following modification of that theory.

Suppose the basilar membrane to be uncoiled and looked at from above, as in fig. 2, then since it is tense in its transverse and not in its longitudinal direction, we may look upon it as a series of minute strips of membrane, or, as Helmholtz considers, of strings, running from the tip of the osseous spiral lamina to the ligamentum spirale. And each of these strips may have a vibration-frequency such that it is set in sympathetic vibration by sound vibrations of exactly the same frequency.

Suppose a note is sounded of a frequency exactly as that of the strip at AA (fig. 2, p. 335), then that strip or fibre will vibrate with a considerable amplitude, and the nerve in connection with the hair-cells at A will be stimulated. Now Helmholtz considered that this (or at most two or three fibres) was all the portion of the membrane that would vibrate, and Rutherford made the well-founded objection that the fibre could not vibrate alone, but would drag the portion of the membrane on each side along with it. If this were the case, then, when a pure tone was sounded, we should hear that tone strongly, and a few higher and lower in pitch along with it more feebly.

It appears to the writer that if the fibre at AA has a vibration-frequency exactly the same as the note sounded then, it will vibrate with a certain amplitude. But since the fibre at BB is only a very minute amount longer, and subject to a tension only a minute degree less than AA, it also will vibrate in sympathy with the note, though not with quite so great an amplitude. Similarly the fibre at DD will vibrate in sympathy with the same note, but with an amplitude less than BB, and so on, until at, say, EE, the amplitude of movement of the fibre will be so small as to be negligible.

In the same way, if we proceed down the basilar membrane, the fibre CC, being a minute amount shorter, and subject to tension a minute amount greater than AA, will vibrate in sympathy with the note, but with an amplitude less than AA. So also the fibre at GG will vibrate in sympathy with the note, but with less amplitude than CC, and so on until at FF the vibrations are so small as to be negligible.

It must be added that this is not a matter of conjecture, but is strictly in accord with the laws of sympathetic resonance.

Suppose now that we make a longitudinal section through the basilar membrane when the same note was being sounded, we should find that, at the end of one phase of the wave, it was

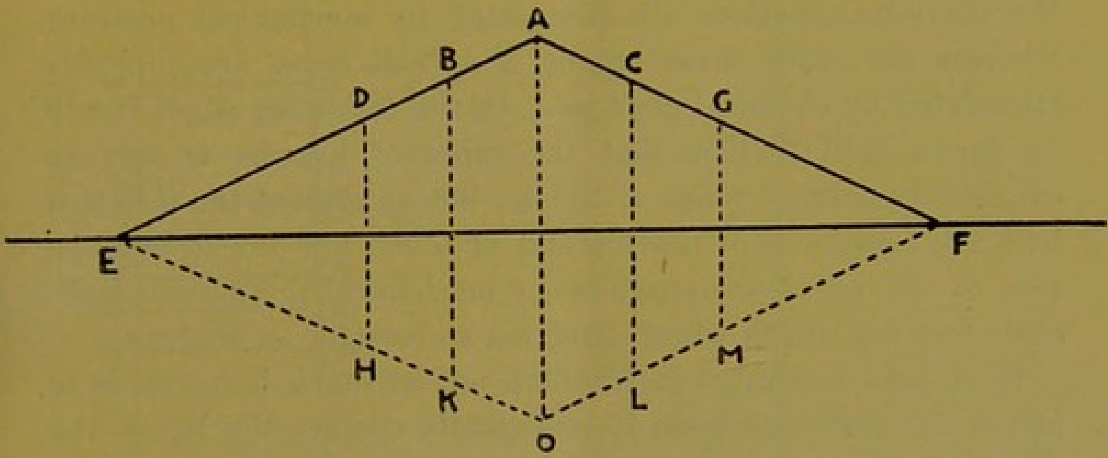

Fig. 3.

raised from its position of rest and had become bent, the bend being of course at the point where the fibre AA was cut transversely, as in fig. 3. At the end of the opposite phase of the wave the bend would occur at a point exactly opposite.

The whole amplitude of the movement of the fibre A would therefore be represented by the line AO, that of the fibre B by the line BK, and so on, until at the points E and F the fibres, having a vibration-frequency so far removed from the note, would move to an extent so small as to be negligible.

When the fibres move as described, then the hair-cells attached to their inner extremities would be carried along with them; so that in the movement upwards the hairs of the hair-cells would be pressed against the tectorial membrane, and the pressure would necessarily be communicated to the nerve-fibre or fibres terminating at the base of the hair-cells. Hence the nerve-fibre at A would receive the greatest pressure, those at B and C would receive less than that at A, but more than those at D and G, and so on.

Now the question arises, Why is the listener conscious of only one note when, according to the supposition based on perfectly correct acoustical grounds, many nerve-terminations are stimulated? That is to say, why do we not hear more feebly several notes a little lower in pitch than the one sounded, and also some a little higher in pitch?

This is a purely physiological question, and we can get evidence on the subject from another sense very closely allied to that of hearing. I refer to the sense of touch. In both these senses the nerve-terminations are stimulated by mechanical pressure, whereas the other three organs of special sense are probably stimulated by chemical changes. In the following pages it will be shown still further that the sense of hearing is only an exquisitely delicate sense of touch; but at present the fact that both the sensations of hearing and of touch are due to stimulation of the nerve-terminations by mechanical pressure, is sufficient to point out in which direction to look for an analogy.

If we take a pointed instrument, not so sharp, however, as to pierce the skin, and press it very gently against the tip of the finger, we are conscious of pressure at a point. If we press it harder the sensation of a pressure at a point remains, and we may press it so firmly as to render the tissues anæmic for an area of a centimetre in diameter, but still the sensation of pressure at a point remains. Now in this case many nerve-terminations have been stimulated, and that strongly, yet we are quite unconscious of the fact. In other words, although many nerve-terminations have been stimulated, the mind pays no attention to these, but is only conscious of stimulation of that fibre or those fibres which have undergone a maximum degree of stimulation. This is the important point to be kept in mind, and that upon which the whole of the writer's hypothesis depends; but it must be explained that the word maximum is used in its mathematical sense; that is, if immediately on each side of a point of pressure there are other parts which are undergoing less pressure, that point is termed a maximum point, even

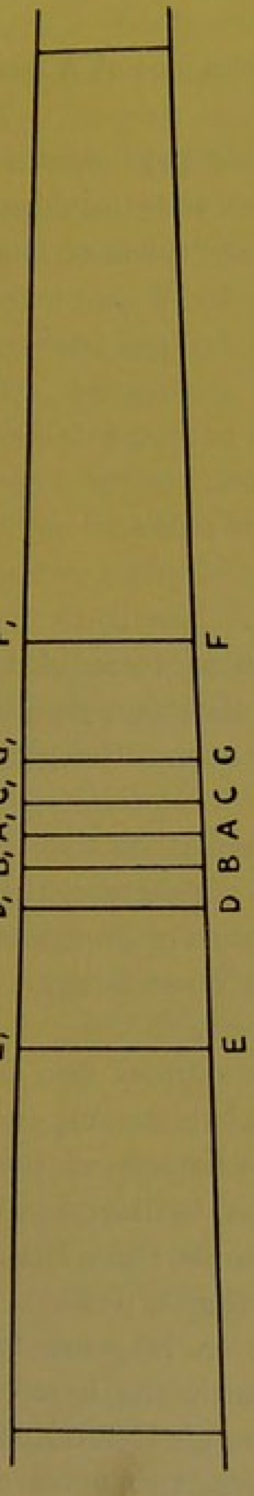

Fig. 2.

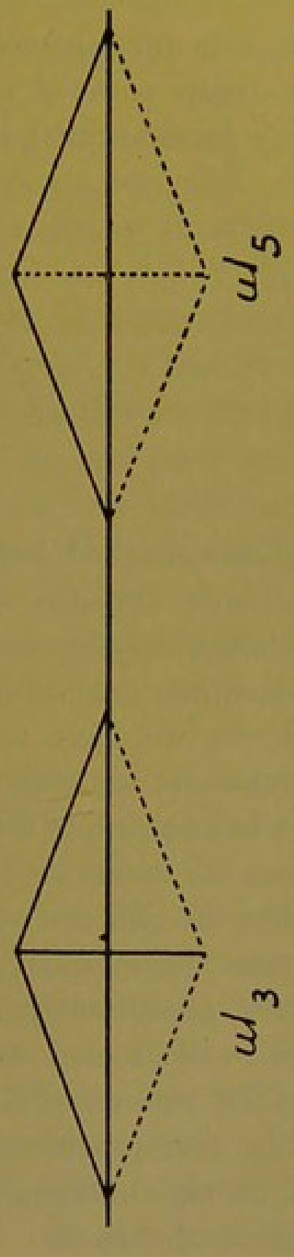

Fig. 5.

although a little distance off there may be another point undergoing greater pressure still. This little matter is not one which is easy to describe, but mathematicians express it concisely by the equation—

$$\frac{dy}{dx} = 0.$$

In fig. 4, for example, there are two maxima, one at A and one at B.

Now, if in the sense of touch the mind only pays attention to the maximum point of stimulation of the nerve-terminations, it is highly probable that the same occurs in the sense of hearing,

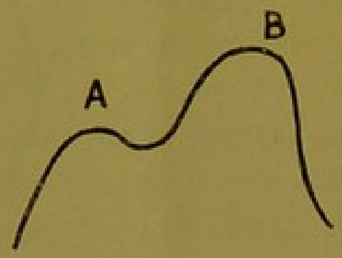

Fig. 4.

which, as remarked before, is only a delicate form of touch. This at once explains why, when a single tone is sounded, the mind should only be conscious of that tone even although other nerve-terminations are being stimulated.

Hitherto we have considered the movement of the basilar membrane and the response of the nervous apparatus only with respect to one simple tone. The subject becomes more interesting when we come to deal with compound tones, because it is here that theories are put to a more exact test.

To take the simplest case first. Let us suppose two simple tones at a considerable interval to be sounded, say ut_3 and ut_5, then we are at once conscious of the co-existence of the two notes. In this case the movements of the basilar membrane would be exactly the same as those for a simple tone, but there would be two maxima as in the diagram (fig. 5, p. 335). One portion of the basilar membrane vibrates in response to the note ut_3, and another portion further towards the base of the cochlea responds to ut_5. There are thus two nerve-terminations stimulated to a maximum, and we hear the two notes corresponding to these nerve-terminations. So also, if three notes are sounded at considerable intervals, we get three points of maximum stimulation and hear three notes of corresponding pitch. So far the case is practically the same as when only one simple tone is sounded. It should be observed, however, that when two or more pure tones at considerable intervals are sounded the result is not a mere noise. The sound may be discordant, but it is still clearly musical.

The interest begins when we have two or more notes sounded which are approximate in pitch. Let us take the case of a mistuned unison first.

Suppose we take two ut_3 forks and mistune one of them so as to give four beats per second when both are sounded. Now the difference in pitch between these two notes is, as above stated, easily recognised if they are sounded separately, but when sounded together the sensation is that of a pure simple tone subject to the interruptions of the silences. It has been stated further that this is an objection to Helmholtz's theory because, if only two nerve-fibres corresponding to the two tones were stimulated, we should be able to note the difference much more easily when the notes were sounded together than when they were sounded separately. This we know to be true of the sense of sight; for example, two shades of a colour may be so close that we cannot tell the difference if they are seen apart, but recognise it at once if we see them together.

If we examine the movements of the basilar membrane in response to the two notes of a mistuned unison according to the theory proposed in this paper, we shall find that the movements produced in the membrane by one note will interfere with those produced by the other note. For example, suppose we sound two notes, one of 256 v.d. and one of 260 v.d. per second, then a certain portion of the basilar membrane will be acted on by both notes; in fig. 6 all that portion lying between the letters H and J will obviously be affected by both notes. Expressed in another way, we may say that any point between H and J will move with an amplitude equal to the sum or difference of the two amplitudes with which it would move in response to each note sounded separately. Thus take any point K; in response to the note of 256 v.d. it would vibrate with an amplitude represented by the line KP, and in response to the note of 260 v.d. it would vibrate with an amplitude represented by the line KO; when both notes were sounded together, and if at any given moment the maximum displacements of the point were both above the position of rest, the point would vibrate with an amplitude represented by KP+KO. If both displacements were below the position of rest the movement would occur below the line of rest, and the amplitude would be represented by −(KO+KP). If one displacement was above and the other below the position of rest, then the amplitude of movement would be represented by KP−KO, or KO−KP, and would be

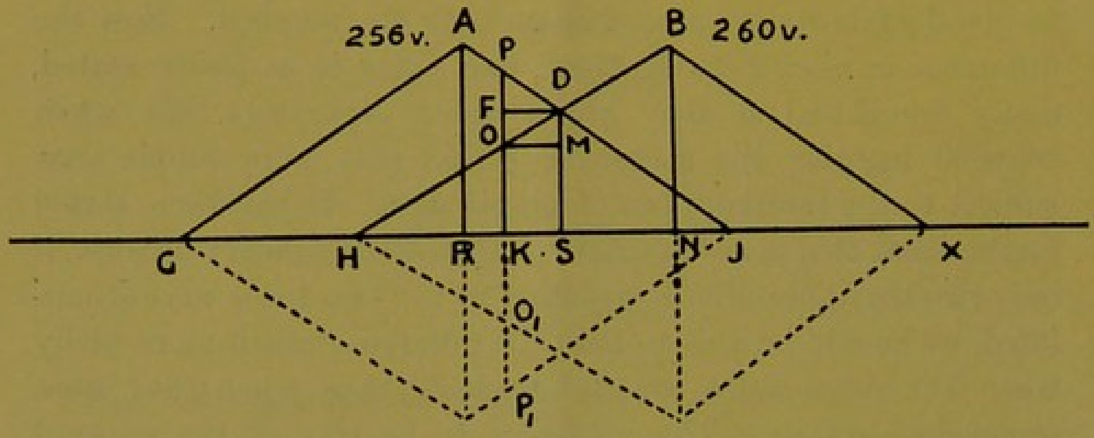

Fig. 6.

above or below the position of rest, that is, would be + or − in co-ordinate geometry, according as KP or KO were the greater.

We can find out the amplitude with which any point between H and J will vibrate as follows:—

First, suppose the intensities of the two notes to be equal, as in fig. 6, so that AR=BN. Since the notes are so close in pitch we may assume that the portions of the basilar membrane raised by each note separately would be equal, *i.e.* GJ=HX.

The amplitude of movement of the point K is represented by KO+KP. Let D be the point at which the two sides AJ and BH of the two equal triangles AGJ and BHX intersect; from D draw DF parallel to KS. The triangles OFD and PDF are equal in every respect.

∴ OF=PF. Draw OM parallel to KS.
KO=SM and FO=DM.
∴ KO=DS−FO.
Similarly KP=DS+FP=DS+FO.
∴ KP+KO=2 DS.

Now wherever K be taken between R and N, FP = FO, therefore the amplitude at K is always equal to 2 DS so long as DS > $\frac{1}{2}$ AR. But 2 DS is the amplitude of the movement at S, and S is a point midway between R and N, the points of the maximum amplitudes of the movements of the membrane caused by two notes separately. Therefore the maximum movements of all the points between R and N are equal, and when the phases of the two notes are in perfect agreement there will be no maximum *point* of movement, but a very small *section* of the basilar membrane will undergo maximum movement. Or, if y be the ordinate and x the abscissa of any point of the membrane between R and N, when it is displaced as described, then—

$$\frac{dy}{dx} = 0.$$

This, I think, is the reason why we cannot analyse the two notes of the mistuned unison when they are within close beating distance and sounded together, although we can distinguish them if sounded separately. In the first case the maximum pressure is never constantly at one point, but oscillates between R and N. In the second case, of course, the point of maximum pressure is constantly at R or N according to the note sounded.

The case discussed is that in which the intensities of the two notes are equal, and where the point midway between their two points of maximum amplitude vibrates with an amplitude of at least one-half the amplitude of movement of either of the maximum points produced by either note singly; or, as in the figure, DS > or $\frac{1}{2}$ AR or BN. Changes in the coefficient of elasticity have been neglected, as the introduction of this factor would only complicate the matter, and it does not affect the principle of the theory.

When the intensities are not the same and the intervals as before, then the condition of affairs is slightly different from that described.

Let R and N, fig. 7, be the two points of maximum amplitude of movement of the membrane when the two notes act separately, and let S be the point of the membrane upon which they both act equally, and let SD = a be the amplitude with which the points would vibrate in response to either note singly, so that under the influence of both notes together it would vibrate with an amplitude of $2a$. Let θ be the angle formed by the line of rest and the position of the basilar membrane when at its greatest displacement in response to one note, and let θ_1 be the angle formed by the line of rest and the basilar membrane at its greatest displacement in response to the other note. Let

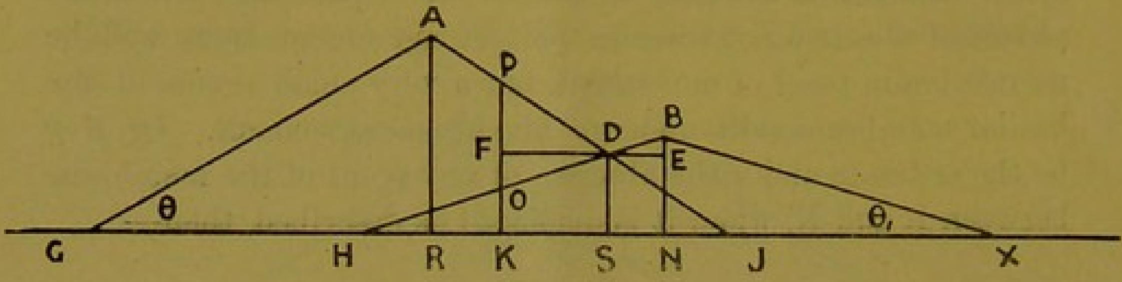

FIG. 7.

RS $=b$, and take any point K between R and S and let RK $=x$. Draw EDF parallel to RN and draw PK perpendicular to RN, intersecting HB at O and EDF at F. Then in response to both notes the point K will vibrate with an amplitude represented by:

KO + KP = DS + FP + DS − OF. = 2 DS + FP − OF. OF = FD tan θ_1 and FP = FD tan θ, and FD = KS = $b-x$ and DS = a,

$\therefore$ KO + KP = $2a+(b-x)$ (tan θ − tan θ_1).

Let y = KO + KP, then :—

$$\frac{dy}{dx} = \tan\theta_1 - \tan\theta.$$

It is evident from inspection that the point of maximum amplitude of movement is R, and the point of maximum pressure on the nerve-termination is therefore at R. But the pressure at R relative to the pressure at the other points is not the same as when a single note is sounded; the relative pressure will vary evidently according to the relative intensity of the two notes. In fig. 7 there is rapid increase in the movement and therefore of the corresponding pressure from G up to A, then a slow decrease from A to B, followed by a rapid decrease from B to T.

The description just given according to the writer's suggestion has been applied only to the movement of the basilar membrane upwards; the movement downwards is, of course, just a reverse copy of that upwards.

Hitherto we have considered a mistuned unison where there has been either no point of maximum amplitude or one in which the slope from the maximum amplitude was very slight on one side; or, using the notation of the differential calculus: $\frac{dy}{dx} = 0$, or a relatively small differential. Further, the section of the membrane undergoing this vibration is very small, so small indeed as closely to approximate to a point, and we therefore hear a pure musical tone, interrupted of course by the silences; but we do not hear two musical tones, because there are not two points of maximum amplitude.

We now proceed to consider the condition of matters which will occur when the two notes become separated by a greater interval. First let us suppose the intensities equal. In this case the points of maximum movement of the two notes separately will be wider apart, but as long as DS (fig. 6) is greater than $\frac{1}{2}$ AR or BN there will still be no *point* of maximum amplitude, but a *section of the membrane* undergoing a movement of maximum amplitude. Further, it is clear that as this section of the membrane becomes greater the amplitude of its movement becomes less. Now this quite agrees with what we find from experiment, for in a mistuned unison the fewer the beats the louder do they become. The fact, however, may perhaps be explained by physical causes acting in the air.

As the notes become still more widely separated, DS becomes less than $\frac{1}{2}$ AR (or BN), as in fig. 8 (p. 345), and now there are two points of maximum amplitude, and we now begin to be able to analyse the sound into its two constituents. It is probable, however, that even for some interval after two points of maximum altitude appear, we are still unable to analyse the compound tone into its constituents, because the dip between the two points is still inconsiderable, and the difference in pressure upon the nerve-terminations correspondingly slight.

Before proceeding further we may again compare the two senses of hearing and touch. When a single pure tone was sounded we saw that it had its analogy in touch when there was contact at a single point on the skin. Have we, then, an analogy in the sense of touch corresponding to the sensation experienced by the ear when two notes at a very slight interval are sounded?

There is no doubt that we have, for it is well known that if the skin is stimulated at two points close together we are not able to distinguish them (*Physiology of the Senses*, M'Kendrick and Snodgrass, p. 54). Thus at the tip of the finger the minimum distance at which two points can be perceived as such is 2–3 mm. In other words, the mind is not able to analyse the variation in pressure, which is in complete agreement with what we find in the case of listening to a mistuned unison. But the similarity between the two senses is even closer, for from experiment the writer has found that the skin of the finger-tip perceives a change in the locality of the stimulation at a distance far less than 2–3 mm. If a point of a needle be pressed gently against the finger-tip, and then be moved and made to press against another point of the skin at about a distance of 1 mm., or even less, we are quite conscious of a change in the locality of the pressure. So that here also we have an analogy with the sense of hearing when we find that though the ear is not able to analyse a note composed of two simple tones if the interval is very small, yet it can recognise a change in the locality of maximum pressure if the two simple tones of the compound one be sounded separately.

So far, therefore, we have a complete analogy at all points between the sense of hearing and that of touch.

Now, as the two points of maximum amplitude of movement of the basilar membrane become further apart it is evident, from inspection of fig. 8 (p. 345), without showing mathematically, that the dip, so to speak, between the two maximum points becomes more and more pronounced, until ultimately the portion of the membrane vibrating in response to one note will not interfere at all with the portion vibrating in response to the other note. Of course the distance between two maximum points at which this may occur must be unknown, and may vary according to the pitch, though, for reasons which will be shown later, there is good reason to believe that at an interval of an octave the vibrating portions of the membrane are still interfering with one another.

When three or more notes are sounded at sufficiently distant intervals, so that their corresponding points of maximum movement in the basilar membrane are sufficiently far apart as not to interfere too much with one another, then we are able to analyse the compound note into its three constituents, and so on for a larger number of notes. In these cases, of course, we have the analogy in the sense of touch that when two or more points of the skin sufficiently far apart are touched we are conscious of contact at two or more points.

The most interesting case is that in which several notes are sounded so near that there are no maximum points, or, at least, none sufficiently pronounced to be perceived as such, and yet sufficiently far apart that a considerable section of the

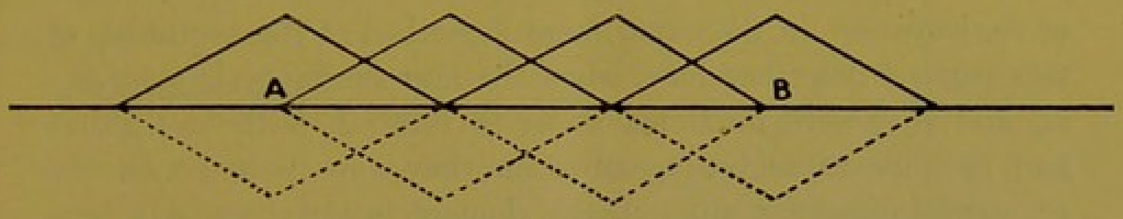

FIG. 9.

membrane vibrates with approximately equal amplitudes in all its parts. Such a case is shown in fig. 9, which represents the movements of the membrane in response to a compound tone produced by four notes of equal intensity at such intervals.

AB is the position of rest of the membrane (in this fig. the displacement both above and below the line of rest is represented).

Fig. 10 represents the resultant maximum movement when the phases are all in complete agreement; all the points in that portion of the membrane between A and B would vibrate with

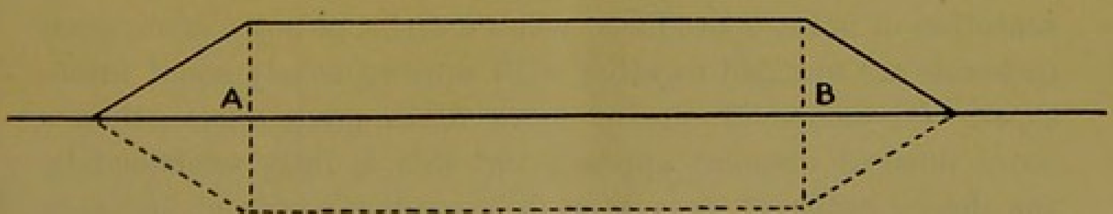

FIG. 10.

the same maximum amplitude. When the phases were not in agreement there would be a maximum point, but it would never for an instant remain constant in position but would oscillate between A and B, and, further, would never have as great an amplitude of movement as that of the portion AB as a whole. The pressure upon the nerve ending in this case, as in the others, varies, of course, as the amplitude of the movement of the basilar membrane. Therefore, the maximum pressure would not be at a point, but along a line; that is, all the nerve-fibres, in connection with the hair-cells between A and B would be stimulated to the same extent. It corresponds, therefore, with pressure along a line in the sense of touch; in other words, with a sharp edge applied to the skin.

I believe that in this case the sensation we experience in the case of hearing is that of a noise. Nor is this entirely a matter of conjecture. In the experiment described at the beginning of this paper I described how, when the four tuning-forks (two ut_4, si_3, and $si_3\flat$) were mistuned so as to interfere with each other and produce rapid beats, and when they were bowed with the requisite intensities, the musical element in the sound was very small and the noisy element prominent. On the other hand, when four forks, each an octave above the preceding one, were weighted so as to produce rapid beats, the musical element predominated. Even in this case the slight element of noise is probably explained by the fact that the upper partials of the lower pitch-forks would have a vibrating-frequency closely approximating those of the highly-pitched forks. These experiments are, of course, rough, because of the difficulty of getting the suitable intervals and intensities. I am at present constructing a large series of pipes covering about an octave, and by this means I hope to investigate the causation of noise with more accuracy. The experiments, however, go to show that the sensation of noise is produced when a series of notes at no great intervals are sounded together with approximately equal intensities. Of course, if one or more notes predominate, then a more musical element appears, and this is fully explained by the theory proposed, because such a predominance of one note will call forth a corresponding increase in the amplitude of movement at a point in the basilar membrane.

On similar grounds it would appear that what is termed a discord in music, is produced in a similar way to a noise. In this case either the interval between the two notes themselves, or between some of their partials, is too small to allow of well-pronounced points of maximum amplitude of movement of the membrane, or too large to cause merely an increase and diminu-

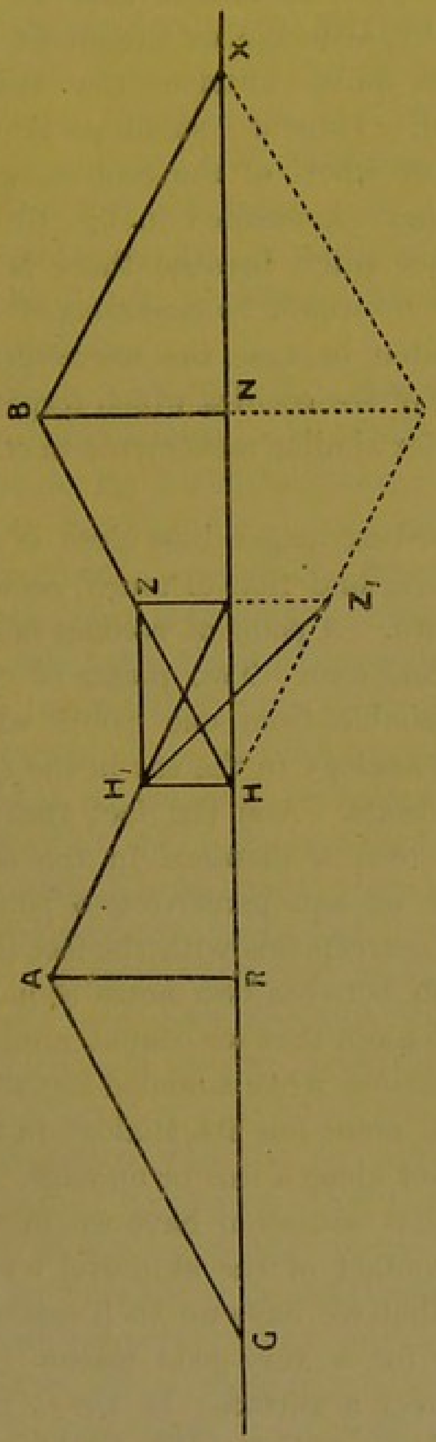

FIG. 8.

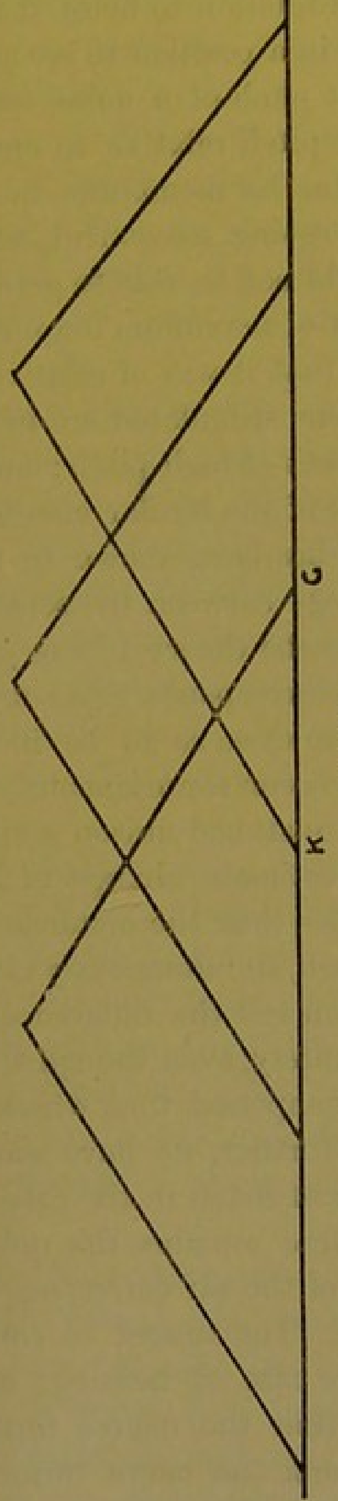

FIG. 11.

tion in the intensity of the musical sound, such as is produced by two notes within close beating distance. A discord, according to this view, is a musical sound on its way to become a noise, and I think our sensations would bear out the statement above arrived at on theoretical grounds.

In relation to noise, it is very interesting to note that we are now in a position to see clearly why, although we cannot fix the exact pitch of a noise, we are yet quite conscious that noises have pitch relative to one another. Thus, if a small portion of the basilar membrane in the lower whorl of the cochlea were undergoing movement, such as that represented in fig. 10, we should not be able to give its exact pitch, because there is no point of maximum amplitude, but we would be conscious of the fact that it was of relative high pitch, because the nerve-terminations stimulated are in the part of the cochlea which responds to tones of high pitch; and so on for similar movements in other parts of the basilar membrane.

It has been shown in the preceding pages how close is the analogy between the sense of hearing and that of touch, according to the theory I have put forward. A point of contact in the skin corresponds to a simple musical tone. Two points of contact so close as to be indistinguishable from one point when both occur simultaneously, has its analogy in the ear in the case of a mistuned unison giving slow beats. And the fact that we can estimate change of locality over a distance in the skin smaller than the distance at which we can perceive two points, as such, simultaneously estimated, corresponds with the fact that we can tell the difference in pitch between two notes sounded separately, even though they be so close that we cannot analyse the compound tone which they produce when sounded together. And further, we have seen that a noise has its analogy in the sense of touch in the case of contact along a line or an edge.

There remains the question, what sensation have we in the case of the ear corresponding to contact of the skin over a surface? The answer of course is, that we have no such analogy in the case of hearing; and this for a very good reason. In the skin the nerves terminate over a surface; in the organ of Corti the nerve terminates along a line. We could not, therefore, have an analogy in the sense of hearing corresponding to the sensation of contact over a surface in the case of touch. This apparent exception, therefore, may be said to support the close analogy between touch and hearing, as explained in the preceding pages.

There remains now only the consideration, how does the theory agree with the fact shown by Lord Kelvin, that under certain circumstances the ear is able to appreciate change of phase? Helmholtz's theory does not explain this.

Taking first the case of a mistuned unison giving slow beats (fig. 6). Since the maximum points are close together, it is evident that changes of phase will merely cause an increase or diminution in the intensity of the sound, because the portions of the basilar membrane acted on by the two notes are almost identical.

When, however, the interval becomes greater, the basilar membrane begins to be acted on in a more irregular manner. Thus, in fig. 8 the membrane is raised from G to A, then it slopes down with the same inclination from A to H_1; now at this point a change in the sharpness of the inclination will occur. For, if the displacements of the membrane produced by the two notes are in the same direction, then the inclination will become less sharp, as, for example, from H_1 to Z. If the displacements are in the opposite direction, the inclination will become more abrupt, as from H_1 to Z_1.

Now, if the cycle is completed very rapidly, as in a perfect harmony, *e.g.* an octave, these changes will be so rapid that we cannot perceive them, but if the cycle is changed slowly, then a given displacement of the membrane will only recur at relatively long intervals, and the mind is able to appreciate the variations in pressure upon the nerve-terminations. This occurs when the harmony is imperfect. We see here, therefore, the explanation why the ear appreciates change of phase only on imperfect harmonies other than unison.

Lord Kelvin further noticed the fact that these changes of phase were much more pronounced in the case of mistuned multiple harmonies than mistuned binaries, except the binary octave. Now, according to the theory proposed, it is clear that if we used three notes, each of which acted in part upon the same portion of the basilar membrane, the movements would be still more pronounced, and the pressure variations on the nerve-terminations would be more marked.

Thus in fig. 11 the portion of the membrane between K and G would be subject to very great variations in the extent of its movements, and its inclination to the line of rest and the nerve-terminations would be subjected to very pronounced variations in pressure. As in the case of a binary harmony, it is essential that the cycle should change slowly.

As the intervals become greater than an octave, the ear gradually becomes less able to perceive difference of phase. Thus if the harmony 1 : 3 be mistuned, the change of phase during the cycle is by no means so easily perceived by the ear (Lord Kelvin, *loc. cit.*), and as we pass to greater intervals, still the ear no longer perceives a difference in the character of the sound produced by differences of phase. It is the fact that the ear can perceive these differences at intervals of an octave, and even a little more, that leads the writer to the conjecture that the portion of the basilar membrane which responds sensibly to a single note, covers at least an octave. That is to say, if a certain note produces a maximum movement of the basilar membrane at a certain point, then the membrane is vibrating sensibly, though, of course, with much less amplitude, at a point which would be the maximum amplitude of movement called forth by the octave of the note referred to. This is, however, as remarked above, a matter of conjecture.

In the preceding pages it has been shown how the basilar membrane may analyse compound tones into their constituent simple tones, and how under many circumstances, such as noises and mistuned unisons, this analysis does not occur, or at least very imperfectly. It now remains to find out by what means these variations in the amplitude of the movements of the basilar membrane are transformed into nervous impulses. The mechanism by which this is done appears to be simple and singularly beautiful.

Since the hair-cells follow every movement of the basilar membrane, then, in their upward displacement, the hairs, and even to some extent the cells themselves, will be pressed against the tectorial membrane which, in the living condition, lies like a pad over them. In fig. 1 this is not shown, because the section was prepared by the celloidin method which necessitated dehydration, but in sections cut in gum or by other methods without dehydration, the fact is very clearly seen.

When, therefore, the hair-cells are raised against the tectorial membrane, the latter will resist their upward progress and press them down against the nerve-terminations at their bases. Further, the greater the amplitude of movement of the basilar membrane, the greater will be the pressure of the hairs and hair-cells against the tectorial membrane, and the greater will be the stimulation of the nerve-fibre at the base of the hair-cell. When, therefore, a pure tone calls forth a movement of the basilar membrane as in fig. 3, a considerable number of nerve-fibres will be stimulated, but the intensity of the stimulation will be greatest in that nerve-termination which lies at the base of the hair-cell opposite the point of maximum movement of the basilar membrane. In the same way the movements of the membrane called forth by compound tones and noises are transferred into pressures upon the nerve-terminations. Now no more perfect means could be devised for this purpose than the tectorial membrane. It is not attached to the vibrating portion of the cochlea, and it lies over the hairs like a pad, so that the more they are projected upwards against it, the more firmly does it press the hair-cell down against the nerve-termination.

By this means, therefore, the variations in amplitude of movement of the basilar membrane become transformed into exactly corresponding variations of pressure upon the nerve-terminations. These variations of pressure are then sent to the brain, and there analysed in exactly the same way as the pressure variations in the sense of touch are analysed. In fact, the auditory nerve may be looked upon purely as a nerve of touch, but vastly more delicate than any of the other nerves of touch. This is to be expected, for the supply of nerve-fibres to the organ of Corti is far richer than to any part of the skin of corresponding dimensions.

This theory of maximum amplitudes, as it may be termed, appears to account for the known facts concerning the sense of hearing as completely as the theory of Helmholtz, of which it is a modification; and the objections urged against the latter theory cannot be urged against it. Thus many will not admit that each fibre of the basilar membrane or each arch of Corti can move independently of those adjacent to it, which

Helmholtz's theory requires. This objection cannot be urged against the theory proposed in this paper.

Again, Helmholtz's theory does not explain the existence of noise, unless the latter be regarded as purely psychological; and even if that were admitted it does not explain why we cannot, under any circumstances, analyse a noise into its constituent simple tones. The theory proposed in this paper is exactly the reverse in this respect, for supposing it to be correct, then a sound is a noise when we cannot analyse it into its simple constituents; and if we are able to analyse, whether entirely or only partially, then a musical element appears.

In this theory of hearing we have seen a remarkable analogy between that sense and the sense of touch.

The pathological facts concerning the loss of high tones with disease of the lower whorl of the cochlea is equally explicable by either this theory or that of Helmholtz.