CRITICAL REVIEW

THE NEW AUDIOMETRY.

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THE science of sound is a branch of physics which, in recent times, has lagged behind in the phenomenal general advance of other branches of physics. Especially is this true of those parts of the science which bear on the theory of hearing. It must be admitted that there is no general agreement as to the mechanism by which sound impulses are converted into sensations of sound, and no student of physiology can fail to notice the uncertainty and confusion with which this important branch of the subject is treated in the text-books. That this is so is due very largely to the lack of precision in the data on which the various theories of hearing must necessarily be based, and particularly to the lack of accurate measurements of intensity of sound, and of the means of production of a continuous series of pure tones of graduated pitch.

Scientific workers in the United States are making a determined and well-organised attempt to remedy this unsatisfactory state of affairs, and to bring the subject of sound and hearing into line with the general advance of science. Good work has been done by Dean and Bunch of Iowa University, under the inspiration of Professor Seashore, by Kranz and others at the Riverbank Research Laboratories, Geneva, under the direction of Professor Sabine, and by Minton and Gordon Wilson at Chicago; various notices of their work have appeared from time to time in this *Journal*. Professor W. Dayton Miller is, of course, a pioneer in this department of research.

The present article is concerned with the researches of a team of workers at the Research Laboratories of the American Telephone and Telegraph Company, New York. The reviewer is indebted to Mr Harvey Fletcher and Mr R. L. Wegel, two leading members of the team, who have very kindly sent him various reprints—fourteen in number—of scientific papers published by themselves and their colleagues during the last three years. These papers embody a mass of most important new facts bearing on audition and the theory of hearing. With regard to the methods employed, the most original feature is the almost complete elimination of all mechanical contrivances. The minute physical forces which they set themselves to manipulate and to measure are treated almost entirely as electrical quantities, in which form they are both more accurately controllable and measureable.

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The New Audiometry

Audiometry.—It will be useful to give first a summary of the technical capabilities claimed for the apparatus used:—

(1) A series of pure tones can be produced which can be varied in pitch in short steps throughout the whole scale of audibility.
(2) The loudness of each tone can be varied continuously throughout the whole scale of audibility.
(3) The loudness of the tone impinging on the ear drum can be measured in absolute units (dynes).
(4) By means of "wave filters" components of a compound tone of any particular frequency may be eliminated before the compound wave reaches the receiver.
(5) The components of a compound tone can be completely analysed with respect to frequency and intensity by means of electric harmonic analysers.
(6) Compound tones can be synthesised from pure tones of any required frequency, intensity, or phase relationship.

If we can accept without reserve these perfections of technique, we need no longer be in any doubt as to the actual facts of audition. It only remains to classify and interpret correctly the facts as they emerge from this wonderful machine. When we consider that the workers in question are a body of skilled electrical engineers whose primary business is, as one of them says, to "deliver the goods," which in this case consist of reproduced speech or music, on a huge commercial scale, and with as little distortion as possible, we must admit their qualifications for this research are unquestionable, and that any claims they put forward are likely to be well founded.

The reviewer is not capable of explaining fully the technical details of the apparatus in use. Indeed, only the general outline is given in the papers to hand, but this is sufficient for our purpose. The principles on which the audiometer works will be more or less familiar to those who have interested themselves in radio-telephony.

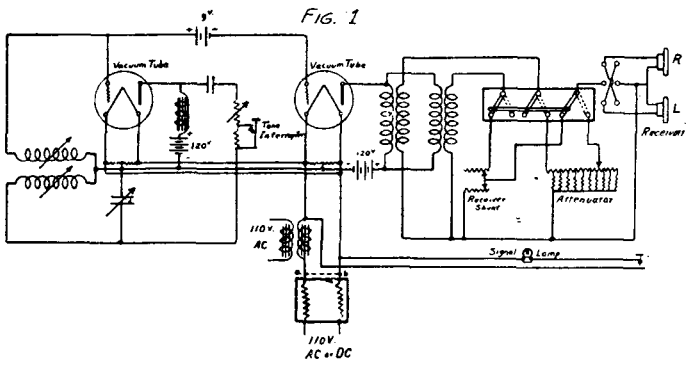
The sound generator (or rather generator of harmonic electric waves) is a "vacuum oscillor tube," better known to wireless enthusiasts as a "valve." This is capable of furnishing a very pure tone even without wave filters, since particular care is taken in the selection of a circuit, coils, and condensers.* The intensity is controlled by "attenuators," or arrangements of switches and graduated resistances by which the current can be varied from below minimum audibility up to painful intensity. The circuit is furnished with capacity (condensers) and inductance, by varying which the frequency of the harmonic wave can be varied in small steps from 60 to 4000 double vibrations (or cycles) per second (Fig. 1).

* See p. 16 in Reference 2.

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In order to graduate the intensities in absolute units, the current is transformed into sound waves in air by means of the "thermophone." This beautiful little contrivance was demonstrated, in 1922, at the Annual Meeting of the British Association for the Advancement of Science, and its principles are well known. It consists of an ear-piece shaped like a tubular telephone receiver, which fits closely to the ear of the observer, so as to form a closed air chamber. Stretched across it is a very delicate metallic conductor (a square of gold leaf or coils of very fine wire) through which the telephone current passes. The surface of the gold leaf or coil of wire is so great, in proportion to its mass, that any heating effect the passage of the current produces in the wire is instantaneously conducted to the air surrounding it. Each increment of the current causes an expansion of the air, thus giving

AUDIOMETER
CIRCUIT DIAGRAM
FIG. 1



rise to a sound wave. The sound waves reproduce promptly and exactly each variation of the current in the telephone circuit. The special merit of the thermophone is that the proportion of the current converted into heat is very constant for all intensities. As the energy content of the current is measurable, that of the sound waves is also known, and can be expressed in absolute units (ergs). The alternation of pressure of air in dynes is proportional to the square root of the energy contents.

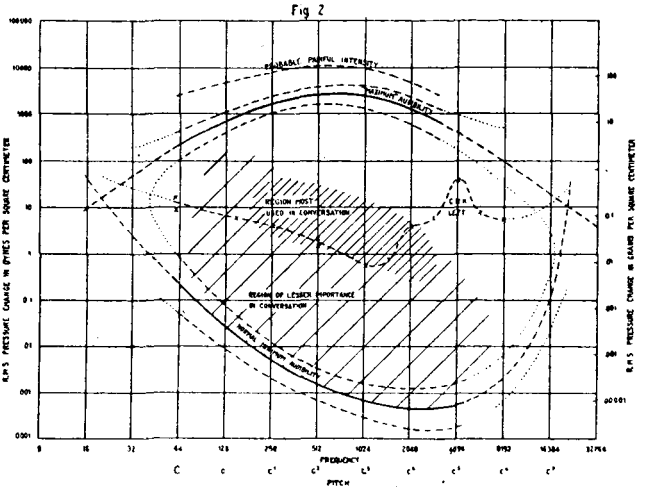
The disadvantage of the thermophone is that it can only be used for currents of low intensity, in the region of minimum audibility. For greater intensities a high quality telephone receiver is used. This can be calibrated in absolute units by comparison with the thermophone, so that the numerical relationship between the current passing through the receiver and the intensity of sound produced is known.

The method of testing is to vary the intensity of the sound con-

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ducted to the ear of the subject whilst keeping the frequency constant; and then to pass by small steps to other frequencies and repeat the process. The range of frequencies tested is from 60 to 4000 cycles per second. For each frequency the *minimum* and *maximum* audibility is measured in absolute units. The *maximum audibility* is defined as the point at which the pressure variations of the air begin to be *felt* as well as heard. (A better term is perhaps *threshold of feeling*.) Sound becomes painful at intensities a little beyond this point. The results are plotted as an *audigram* on a chart as shown in the figure (Fig. 2).

Fig 2



Explanation of the Audiometric Chart.—It will be seen that the base line represents pitch or frequency, and is divided off in octaves (abscissæ). The vertical lines (ordinates) represent intensity of the sound measured in degrees of pressure variation per square centimetre of surface. Equal divisions represent an increase in geometrical progression, *i.e.*, each represents an increase of ten times the previous intensity of the sound. Both the abscissæ and ordinates are thus graduated as a logarithmic scale, the former being to the base 2, and the latter to the base 10. The observers are agreed that the sensation of hearing conforms in a very striking manner to Weber's law, viz., "the increase of stimulus necessary to produce an appreciable increase in sensation bears a constant ratio to the total stimulus, *i.e.*, is always the same fraction of the total intensity of the stimulus." *

The range of hearing is thus represented by an area on the chart enclosed between the two curved lines of minimum and maximum

* See p. 6 in Reference 2, and p. 340 in Reference 3.

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audibility. The thick lines above and below represent the average findings for a number of normal ears, whilst the dotted lines running parallel to the thick lines show approximately the range of variation of the minimum and maximum in normal individuals.

Lower and Upper Limits of Frequency.—"As frequency is decreased the sensations of feeling become milder until at frequencies around 60 cycles they are sensible as a flutter, normally quite distinguishable from the sense of audition. As the frequency is further decreased to a point where the hearing and feeling lines intersect, it is difficult to distinguish between the sense of hearing and that of feeling. The low point of intersection of the two normal curves of minimum audibility and feeling may, therefore, be defined arbitrarily as the lower tone limit of audibility. The data indicate the point to be in the neighbourhood of 20 cycles per second. A similar intersection of the two curves occurs at a very high frequency. The upper tone limit seems to be in the neighbourhood of 20,000 cycles." * It will be noticed that the upper and lower limits are functions of intensity as well as frequency. For the full range of pitch a sound of intensity of approximately 10 dynes must be used for testing.

Range of Intensity of Sound.—The range of magnitudes to be deduced from the audigram is extraordinary and somewhat disconcerting. The shaded area in the middle of the chart (Fig. 2) represents the range of pitch and intensity most used in conversation. Sounds used in conversational speech are approximately 1,000 times more intense than minimum audibility, and there is a similar range above this level, up to maximum audibility, *i.e.*, a total range of audible sound 10^6 (a million to 1). (The energy range is the square of this, *i.e.*, a million million to 1.)

Minimum Audibility as a Function of Pitch.—The chart shows the very striking difference of level of minimum audibility at different pitch levels. For example, at 64 cycles per second the minimum is 1000 times greater than at 2000 cycles. Above 5000 cycles the minimum line again rises sharply.

Deafness.—Deafness is indicated on the chart by a raising of the line of minimum audibility. The irregular dotted line crossing the centre of the audigram in Fig. 2 represents the diminution of hearing in a deaf subject. Below the level of the line hearing is absent. In this case the line encroaches on the speech area. The individual has some difficulty in understanding speech. The threshold of feeling is not greatly different in the deaf and in the normal hearing subjects.

The chart affords a possible method of computing degrees of deafness.† Harvey Fletcher suggests as a definition, "the percentage of the total number of distinguishable pure tones audible to a person

* See p. 8 in Reference 2. † See p. 15 in Reference 7.

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with normal hearing, that can be sensed by a deaf person"; in other words, the proportion of the area covered by the normal audigram to that above the line of minimum hearing in the deaf person. Deafness will then be computed in terms of the proportion of normal hearing to residual hearing.

A number of charts of different forms of deafness are given,* but, as the writers admit, much more extensive data will be required before conclusions can be drawn. So far as the charts indicate, they do not lend much support to the classical tradition that middle-ear deafness affects the lower, and internal ear or nerve deafness the upper region of the tone scale. They tend to show that in all forms of deafness the middle range of the scale (that most concerned in speech) resists longer than the upper or lower; that evenness of the curve without sudden dips or rises (gaps or islands of hearing) appears to be a general characteristic, and further, that abrupt changes of curvature are more frequently found in the upper than in the middle or lower registers.

Qualitative Defects.—Alteration in the quality tone perception in different regions of the tone scale are found associated with general raising of the minimum audibility line.† A pure tone may be heard merely as a noise at one level, or at another level as a tone mixed with noise or with beats.

The clinical application of the new audiometry is a large field awaiting cultivation. This will be the province of the clinician. It is evident that the "audigram" affords a convenient uniform method of accurately recording case findings, of estimating the degree of deafness, and of comparing the state of the hearing of patients from time to time. When a sufficient number of records are available, classification into "types" will become possible. A beginning has already been made in the utilisation of the "audigram" as an indicator of the type of acoustic aid most suitable for the case.‡ It is pointed out, however, that all "aids" have their limitations. It is possible to raise the energy content of sound vibrations over the whole range of speech frequencies by a telephone hearing aid, but if the deafness is severe the preponderating speech tones will have to be raised above the level of maximum audition (or threshold of feeling) before the less powerful constituents have reached the minimum audition line, and the result will be distressing to the patient. The intelligibility and character of the speech depend more on the less powerful tones (consonants) than on the more powerful tones (vowels).

Theory of Hearing.—The present significance of the new method rests more on the wealth of new facts bearing on the theory of hearing than on clinical data.

* See pp. 22-34 in Reference 2, and p. 16 in Reference 7.
† See p. 6 in Reference 4. ‡ See p. 13 in Reference 12.

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George Wilkinson

Number of Distinguishable Tones.—The writers compute (1) the number of distinguishable degrees of loudness of tone at constant frequency; (2) the number of distinguishable pitches at one *level* of loudness. As will be seen from the chart, both these relationships vary in the different horizontal and vertical levels. The writers find that, in the middle portion of the scale, the amount of the increase of intensity of sound impulse which is just distinguishable as an increase of loudness of the sensation is 10 per cent., *i.e.*, the stimulus must be increased by 1/10 of its previous intensity.*

With regard to the number of distinguishable pitches, for frequencies between 400 and 5000 the ratio for tones of medium intensity is fairly constant at 0.003. This gives 266 distinguishable pitches per octave over a range of three and a half octaves. Each tone area occupies approximately 0.02 mm. along the length of the basilar membrane.† This would give a total of about 1550 distinguishable pitches, a number much below previous computations (4000 to 8000). The discrepancy may be accounted for by the fact that it is easy to interpret small differences of loudness of tones of the same frequency as small differences of pitch. This may have given rise to an overestimation of the number of distinguishable tones, as in earlier observations no attention was paid to the comparison of tones at one fixed level of intensity. Grouping together distinguishable degrees of loudness and of pitch yields a quotient of 300,000 separate "units of sensation."

"Non-linear Conduction" of Sound in the Ear.—A number of observations are recorded to show that there is "non-linear" conduction of sound impulses through the middle and internal ear to the sensory terminals; by this is meant that the sensations of pitch evoked do not exactly correspond to the frequencies of the sound wave impinging on the ear. This is particularly the case for stimuli of considerable intensity.

Subjective harmonics are introduced when a pure tone of medium or high intensity is conducted to the ear. These can be detected by the method of beats.‡ The same applies to *combination tones* (the differential and summational) which are audible when two pure tones of different frequencies are conducted to the ear at the same time. No attempt is made to explain the actual mechanism of the production of such subjective tones. We learn, however, the interesting fact that similar secondary harmonics occur in the vacuum oscillator tube when "overloaded," *i.e.*, when the current passed through it exceeds its proper capacity,§ and that the presence of combination tones in

* See p. 29 in Reference 7. † See p. 14 in Reference 8.
‡ See pp. 6 and 7 in Reference 8, and p. 25 in Reference 7.
§ See p. 3 in Reference 11.

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an overloaded circuit can be recognised by a "detector tube." It is interesting to know that these imperfections, which have been so freely quoted as arguments against the resonance view of the cochlea, should be found to be inherent in resonators of an entirely different character.

Masking.—One paper* is devoted to the elucidation of the phenomena first described by A. M. Mayer, viz., that a low-pitched sound can obliterate a high-pitched one, but that a high-pitched sound cannot mask a low-pitched one. The following conclusions are arrived at: (1) When the masking tone is loud, tones of higher frequency are more masked than those of lower frequency; when weak there is little difference. (2) The nearer the two tones approximate in pitch the more readily is the weaker tone masked by the stronger (provided they are not sufficiently near in pitch to give perceptible beats). (3) When the two tones are introduced into opposite ears masking is very slight, and may be accounted for by conduction of the louder tone across the skull to the opposite ear. (4) At high frequencies the difference tone is better heard than the masked tone.

Binaural Hearing.†—It is a remarkable fact that persons deaf in one ear can locate familiar complex sounds almost as well as those with binaural hearing. They cannot, however, locate pure tones. This points to monaural localisation of sound being due to alteration of the relative intensity of the different harmonic components of the compound tones, according to the position of the head in space. Thus, with the hearing ear turned away from the source of sound, the high frequency components of the sound cast more shadow than the low frequency, and so are less heard. The writers (Hartley and Fry) also consider that there may be a sense of the altered relationship between the phases of the different component waves. If this has any bearing on sound localisation it must be subconscious, as in another place it is admitted that changes of phase relationship of the constituents of the compound tone produce no noticeable effect on the ear, *i.e.*, they do not alter the character of the sound heard.‡ With a very complex collection of sounds, such as a band of music, the conduction of the sounds separately to the two ears through tubes of unequal length upsets the phase relationship of the sounds and leads to a confusion of sense of direction.§

Physical Criteria for determining Musical Pitch.‖—The important rôle of the subjective difference tone in music is well illustrated by some experiments performed by Harvey Fletcher. We

* See References 8 and 15.
† See Reference 5.
‡ See p. 3 in Reference 11.
§ See p. 8 in Reference 5.
‖ See Reference 9.

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judge the pitch of a complex tone by that of its lowest component, or fundamental, even though in many cases, such as the tones of the cello-organ pipe, or the vowel *ah*, some of the overtones are actually more powerful than the fundamental. A complete analysis of these compound tones is made possible by an electric harmonic analyser, on the resonance principle. (As Helmholtz has said, "The *only known* method by which compound periodic motion can be analysed into simpler pendular motion is by means of sympathetic vibration." This statement holds good up to the present.) By electric wave filters any range of frequencies can be eliminated from the compound tone before it passes into the telephone receiver. It was found, for example, with the clarionet tone, that the fundamental and four lower harmonics could be deleted without altering the pitch of the sound. The case is similar for certain vowel sounds. The explanation given is that the subjective difference tones evoked by each successive pair of the remaining partials supplied the place of the fundamental, thus causing the sense of pitch to remain unaltered. Owing to the lesser sensibility of the ear for low tones, it is probable that the fundamental of most musical tones would be only slightly appreciable were it not reinforced by the difference tone.

Bearing of Findings on the Theory of Hearing.—The writers, like all those who have set themselves actually to interpret the fact of hearing rather than to avoid the difficulties of such interpretations, are forced to assume that the pitch of pure tones is determined by the level of maximum response of the basilar membrane, the high tones stimulating regions near the base, and low tones the regions nearer the apex of the cochlea.* In this conclusion they occupy common ground with the advocates of the resonance theory. The mechanism of this modified resonance they explain somewhat on the lines of Roaf's "dynamical theory." They assume very wide excitation of the basilar membrane for each and every pitch, and free overlapping of the areas of resonance. This gives rise to subjective combination tones. It is rather difficult to believe that an instrument of the most delicate precision, like the cochlea, can possibly be constructed on such free and easy lines. Masking of one tone by another occurs when the peak of the masked tone is submerged in the rising slope of the masking tone. The obliteration of a higher pitched tone more readily than a lower one by the masking tone is accounted for by the generation of harmonics in the ear, which act as secondary masking tones for tones of higher pitch.

To the reviewer it appears that undue emphasis is given to these subjective harmonics. Each and every pure tone which impinges on the cochlea is supposed to give rise to a whole series of maxima of

* See p. 29 in Reference 7.

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vibration, corresponding to the harmonics of the tone. If this is so, how do we distinguish between a "rich" tone, in which the harmonics are actually present in the exciting air wave, and a "thin" tone, in which the note is pure but the harmonics absent?

The writers of these papers are practical men, and one notices that they exercise considerable restraint in making theoretical deductions from the facts observed. Indeed, one may say of these theoretical deductions that they add point to a very apt remark of one of the writers, viz., that in this perennial discussion the physiologists never appear to understand the physical problems, and the physicists never seem to have thoroughly grasped the structure of the ear, or the nervous activities involved in the process of interpretation. This would explain the absence of any reference to the graduation of tension of the basilar fibres by means of the spiral ligament, which is almost certainly the most important factor in differentiating the pitch levels.* Neither has the question of the inertia of the vibrating columns of fluid in the cochlea received full consideration.

Speech.—One of the most valuable features of these researches is the beautiful detailed analysis they afford of the various elements of speech. The frequencies used in speech vary from 60 to 6000 cycles, the maximum of the energy being at about 200 cycles. The vowels carry most of the energy of speech, and their important frequencies lie below 3000 cycles. The higher partials between 3000 and 6000 cycles concern the consonants mostly, and are of the greatest importance for the correct interpretation of speech, and for giving individual character to the voice. The enormous preponderance of energy in the lower frequencies is discounted by reason of the lower sensibility of the ear for low-pitched tones.

It is not possible to enter in detail into the analysis of vowel sounds given in these papers.† Suffice it to say that the results arrived at agree in the main with those of Helmholtz and with the later work of Professor Miller, and confirm the Helmholtz theory of

* The reviewer has received a paper from Mr R. G. Wegel which has not yet appeared in print, which contains the following remarks bearing on this point. "Helmholtz . . . gave rather extended mathematical treatment of a tapered membrane with high lateral stiffness and small longitudinal stiffness. The statement of competent physiologists and histologists that the basilar membrane, like all living tissues of the body, is normally under such tension, or in a tonic state, should be accepted by physicists." . . . "In order to explain the intimate mechanism of the cochlea, a theory qualitatively like that of Wilkinson and Gray seems to be necessary. It requires a graduation in tension of the fibres of the basilar membrane."

† References 6, 10, 11, 14.

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"fixed resonance of the vowel partials," or, more correctly, fixed ranges of pitch over which the partials characteristic of the particular vowels are reinforced by the resonance cavities of the pharynx and mouth. Their division of the vowels according to single or double ranges of resonance also agree with that of Helmholtz.

It would seem that if technical skill, enthusiasm, and hard work can solve the knotty problems connected with hearing and speech, there is good hope of their being completely elucidated in the near future.

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