THE RELATIVE SENSITIVITY OF THE EAR AT DIFFERENT LEVELS OF LOUDNESS.

By Donald MacKenzie.

Synopsis.

Alternation Phonometer for Balancing the Loudness of Tones of Different Pitch.—It has been found that if two tones alternate in the ear at a suitable rate, for instance 25 times a second, the interruptions of the louder tone are the more conspicuous, and it is possible to adjust the relative intensities until the interruptions are equally conspicuous. Two tones when balanced in this way are said to be equally loud. This definition is justified by the fact that if two tones each balance a third tone they are found to balance each other and are also accepted by the ear as equally loud. The electrical circuit, commutating relays, and other apparatus used in making a loudness balance are described. To enable the mean pressure of the sound at the ear drum to be calculated from the electrical energy input, either a thermophone, whose theory is known, or an electromagnetic receiver which had been calibrated (rather imperfectly) by means of an artificial ear cavity and an electrostatic transmitter, was used next the ear. Successive readings usually agree within 5 per cent.

Relative Sensitivity and Sensibility of the Ear, at Various Loudness Levels, for Frequencies of from 100 to 4,000 per Second.—(1) Phonometric comparisons with a thermal receiver were made by ten men and ten women over a limited range of loudness. The results correspond to the equation $\log P_1 = A + B \log P_2$, where P_1 and P_2 are the acoustic pressures, computed from the thermophone theory, of the two balanced tones. This equation is in harmony with Fechner's law. The constant $-A$ is the sensitivity and depends only on the threshold pressures; $1/B$ is the relative sensibility at the two frequencies and is found to be constant, within 10 per cent., for the entire range of frequencies investigated. The curves for men and for women show no systematic differences except at the higher frequencies where resonance of the ear cavity begins to enter. (2) With an electromagnetic receiver a greater loudness range was possible, the pressure being varied up to 20,000 times the threshold values. Of 32 curves obtained with four observers making comparisons against 700 cycles, 25 were straight throughout, in agreement with the thermophone results, and only 7 were distinctly curved near the extremes. The slope at all frequencies is between 0.9 and 1.0; therefore the sensibility is practically uniform, at least to 2,000 cycles and at all loudness levels. No evidence of a phonometric Purkinje effect was observed, but it may be present for pressures near the threshold values. Since the pressures are all computed, the absolute values of A probably contain small systematic errors, but these would not affect the values of B.

INVESTIGATIONS of the sensitivity of the ear at the threshold of audition enjoy the advantage of dealing with one frequency at a time. If it is desired to study ear sensitivity at higher levels, means must be devised for the adjustment of different frequencies to equality of loudness. This done, data may be obtained showing physical intensities of sounds which to the ear are equally loud.

Methods of Sound Comparisons.

The customary method of making loudness balances is to listen to on frequency, then to the other, changing the intensities until the sounds are accepted as equally loud. This measurement can be made with some precision when the sound sources compared are emitting the same note, but is highly uncertain with two notes of different pitches. Aside from the flagging of the attention, there occurs a decay of the sensation,—the mechanism which appreciates loudness is fatigued as the sound continues. Presumably, a different mechanism responds to the second frequency, and the comparison made is between a decayed response to f_1 and a fresh response to f_2. This decay of sensation is readily observed by listening to a steady tone which suffers from time to time interruption for a perceptible interval,—after each interruption the sound seems louder, although the physical intensity has not altered.

It might be affirmed that such an error is offset by the opposite error when the order of the compared frequencies is reversed. In point of fact, however, each change leaves the ear in doubt, and the continuance of the work results in fatigue of all the auditory mechanisms involved. The net result is confusion and the impossibility of obtaining consistent observations.

In optical work, the flicker photometer has made it possible to compare the brightnesses of different colors. A flicker frequency is obtainable such that the colors fuse subjectively, and fluctuations in intensity, as well as the distinction of color, disappear at a definite brightness ratio of the colors compared.

A mechanically operated device, termed a flicker phonometer, has been patented by Heck.[1] The essential feature of this invention, as disclosed in the patent, is a sound-insulated valve automatically rotated at adjustable speed. Two tubes separately receive the sounds it is desired to compare, and each tube conveys an acoustic wave to the rotating valve, by which one tube is opened as the other is closed. Through the valve the tubes discharge sound to horns movable on a track, each facing the inlet to a tube leading to the ear. The claim is made that by proper disposition of the horns and regulation of the valve, pulsations in intensity of the sound reaching the ear can be caused to disappear. It is not apparent that the inventor contemplated the comparison of sounds of widely different pitches.

In this laboratory it has been found possible by electrical means to make use of the perception of flicker in an alternation phonometer. Let two frequencies alternate in the ear at a suitable rate, the intensity of one being maintained constant while the other is varied from faint to loud in comparison. The strong tone is heard plainly interrupted, ac-

[1] Method and Apparatus for Comparing Sounds, C. M. Heck: U. S. Pat. No. 1,356,359, October 19, 1920.

companied by the weaker tone whose interruptions are not clearly distinguished. If now the weak tone is progressively strengthened, its interruptions begin to claim the observer's attention and with further increase in intensity come to overshadow the constant tone just as they were previously overshadowed when faint. A little practice enables the observer to determine a point at which the ear recognizes the two tones as equally interrupted: the attention is here impartially divided, whereas on either side of this point one or the other of the tones makes the stronger impression. Such a point may be identified with a loudness balance.

This statement is justified by the following considerations: (1) unpracticed observers can reproduce their balances within 4 per cent.; (2) on comparing in the usual manner the tones so equated, it is not possible to affirm which is the louder; (3) if in this way f_1 is compared with f_2, and the value of f_2 just found is balanced in turn against f_3, then f_1 and f_3 have values which on direct comparison are found to balance.

Comparisons of this kind avoid difficulties due to the shortness of the persistence of audition and to ear-fatigue. It is, moreover, plausible to urge that the level of any sensation is specified by the attention paid to the stimulus, and it is on this basis that the alternation phonometer is operated.

The Alternation Phonometer.

The currents furnished by two oscillators are alternately impressed on an electrical generator of sound by the armature of a polarized telegraph relay, driven from another such relay at a controllable speed. The relays and their operating circuit are shown in Fig. 1. The use of these relays and the circuit of Fig. 1 were suggested by Dr. W. S. Gorton of this laboratory.

Adjustment is carefully made to secure (within 1 per cent.) equality of duration of contacts on the two sides, and travel time between contacts not greater than 0.002 second. This travel time should not be exceeded, it being desirable to avoid intervals of silence. Within this limit, available sounding intervals range from 0.020 to 0.080 second. An interval of 0.040 second is suitable for frequencies 100 to 4000.

The currents commutated by the driven relay are amplified and supplied either to a gold-leaf thermophone or to an electromagnetic receiver. Fig. 2 is a diagram of the circuit between the relay commutator and the sound generators.

Specimen Results.

In preliminary experiments the procedure was to keep fixed the intensity of one of the tones and vary the other until a balance was reached. Comparisons with the thermophone were made by one observer of a large number of frequencies from 100 to 4,000 cycles. The r.m.s. alternating pressures in the cavity consisting of the thermophone case and the ear canal were computed from a theoretical formula developed by Dr. E. C. Wente.[1]

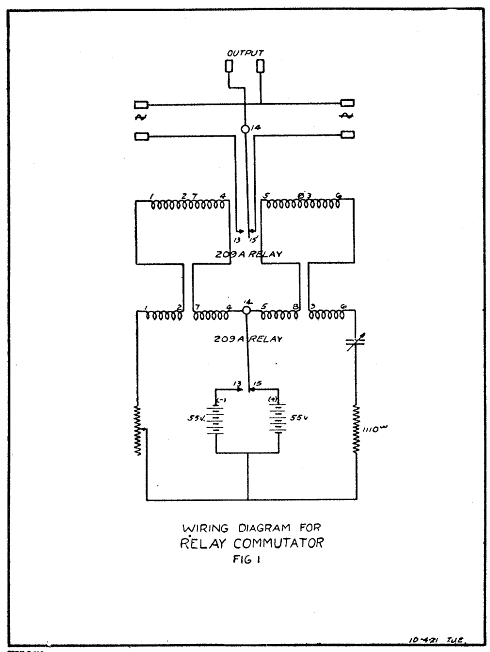

Fig. 1.

If we compare 400 vs. 500, 500 vs. 600, we can infer the result of a direct comparison of 400 vs. 600. Call p_1 the r.m.s. alternating pressure due to a frequency f_1 balanced by p_2 due to f_2, p_3 due to f_3. For the case where $f_1 = 400$, $f_2 = 500$, $f_3 = 600$, we find the following results:

TABLE I.

Observer: T. J. E.

Fixed in Volume.		Varied in Volume.	$\frac{\text{Varied}}{\text{Fixed}}$, Ratio of Pressures at Balance.
400 (f_1)	*vs.*	500	0.76
400	*vs.*	600	0.66
500 (f_2)	*vs.*	400	1.33
500	*vs.*	600	0.84
600 (f_3)	*vs.*	400	1.70
600	*vs.*	500	1.22

Here

$$\frac{p_1}{p_2} = 1.33; \qquad \frac{p_2}{p_3} = 1.22; \qquad \therefore \frac{p_1}{p_3} = 1.62.$$

[1] "The Thermophone," PHYS. REV., 19, pp. 333–345, April, 1922.

By direct comparison,

$$\frac{p_1}{p_3} = 1.70.$$

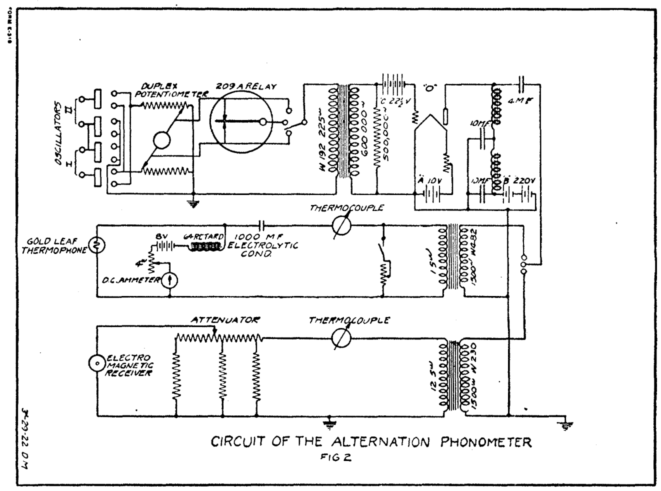

Fig. 2.

Again, when the frequencies exchange rôles, the one previously maintained at fixed volume becoming the variable, we find

$$\frac{p_2}{p_1} = 0.76; \qquad \frac{p_3}{p_2} = 0.84; \qquad \therefore \frac{p_3}{p_1} = 0.64.$$

By direct comparison,

$$\frac{p_3}{p_1} = 0.66.$$

The question arises, does the pressure-ratio at balance vary with the absolute sensation level? To answer this, comparisons of 100 vs. 300 were made at pressures ranging from 1 to 8 dynes/cm.^{2} for 300, 2 to 26 dynes/cm.^{2} for 100. Figs. 3 and 4 are curves representing these data, obtained by two observers.

The data of one observer are plotted in the upper curve of Fig. 3. The lower curve of this figure represents data taken by the same observer, comparing the same frequencies, on the following day. In the second case, a slower rate of commutation was used, the higher speed being judged too high for satisfactory perception of the 100-cycle tone.

The computed points are obtained from a law suggested by a logarithmic plot. It is seen that there is good agreement between the points so computed and those actually observed.

CONCORDANCE WITH FECHNER'S LAW.

Ab initio, we should feel no surprise at finding a logarithmic law. If we are working at a sensation level within the range of Fechner's law, the

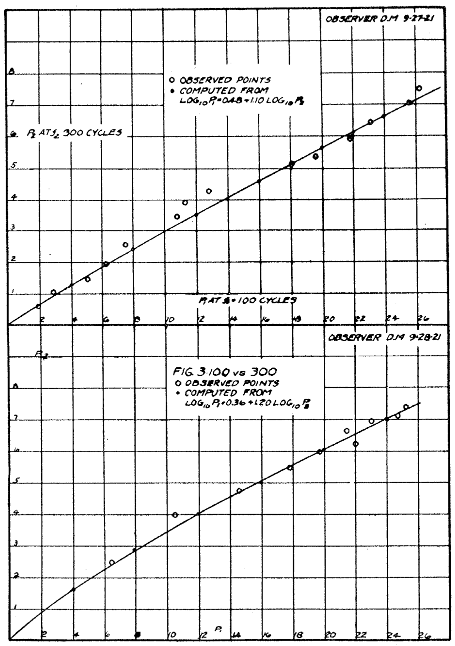

Fig. 3.

sensation should be connected with the stimulus (in this case loudness with pressure) by the relation

$$S = c \log P + a.$$

When two frequencies are at the same loudness,

$$S = c_1 \log P_1 + a_1 = c_2 \log P_2 + a_2$$

or

$$\log P_1 = \frac{a_2 - a_1}{c_1} + \frac{c_2}{c_1} \log P_2.$$

Within the range of validity of such a law, then, we should expect the balances to obey a law of the form

$$\log P_1 = A + B \log P_2.$$

Further evidence confirmed this expectation. Fig. 4 shows logarithmic plots of the data of another observer (T.J.E.) comparing 100 *vs.* 200, 200 *vs.* 300, 100 *vs.* 300. The logarithmic law satisfies observations on frequencies from 100 to 4,000.

At the higher frequencies (2,000 to 4,000) difficulties were found in checking indirect with direct comparisons. If the thermophone case is not held tightly against the ear, a small opening converts the cavity into a Helmholtz resonator and so enhances the effect of the tone whose frequency is the nearer to the natural frequency of the resonating cavity. This source of error may be precluded by care in manipulation. An additional uncertainty is introduced by harmonics contaminating the tones,—this difficulty is remedied by the introduction of filters. Failure to check direct against indirect comparisons may also be due to omitting the precaution to make comparisons at a fixed sensation level.

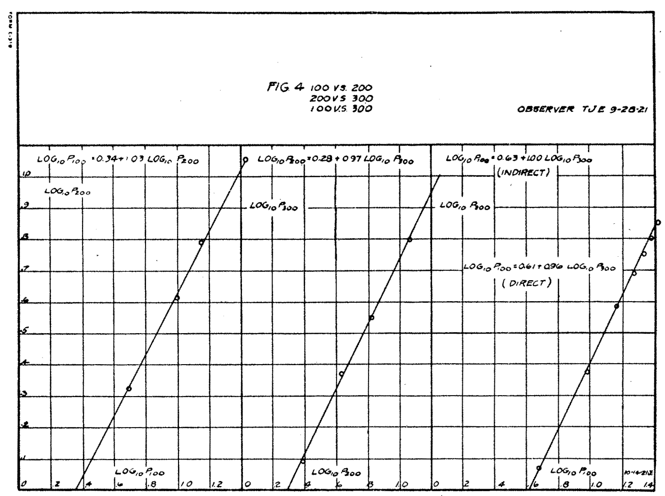

Fig. 4.

When care is taken to conform to these three specifications (tight fit of thermophone against ear, purity of tones compared, fixed level of sensation), the discordance between direct and indirect comparisons is small.

The introduction of a duplex potentiometer, reducing one tone as the other is increased, enables the observations to be made more rapidly and with greater confidence. After each balance, the relays are stopped and the necessary current readings taken. In addition, the observer is given an opportunity to compare the loudnesses of the tones he has adjusted and is asked if his ear accepts them as equal. In nearly every case he finds no fault with the balance. The oscillators are then interchanged on the potentiometer and the observation repeated; the average of the two settings is plotted. A discordance as great as 5 per cent. is uncommon, and does not occur in the absence of distracting room noises.

Suitable changes in currents enable four pairs of balances to be made at levels such that the corresponding points are uniformly spaced on a logarithmic plot.

Ear Surveys with Thermophone.

A survey of 20 ears (of 10 men and 10 women) was carried out with the thermophone. Comparisons were made at four levels involving the frequencies 100 (or 120), 200, 300, 500, 700, 1,000, 1,500, 2,000, 3,000 and 4,000 cycles. Time did not permit all possible combinations, hence in several cases comparisons were made of widely separated frequencies in order to test the claim that direct comparisons may be inferred from indirect.

Of 180 comparisons made by the 20 observers, the results in 93 cases fitted logarithmic straight lines to within the error of the current measurements. No systematic deviations, either for men or women, were found in the other cases. Accordingly, the occasional wide deviations were attributed to experimental blunders. In view of the general confidence in Fechner's law and the concordance with it of most of the results of this survey, the logarithmic equation seems satisfactory.

As an illustration, the results obtained by one observer are given in the table below:

Table II.

Observer: F. H. G.

$$\log_{10} P_1 = A + B \log_{10} P_2.$$

	f_1.	f_2.	A.	B.
(1).........	100	300	0.63	.92
(2).........	200	300	.19	1.00
(3).........	300	500	.30	1.04
(4).........	500	700	.21	.97
(5).........	700	1000	.14	.97
(6).........	1000	1500	.30	1.02
(7).........	1500	2000	.08	.96
(8).........	2000	3000	.13	.93
(9).........	3000	4000	.28	.90
	200	3000	1.41	.91 direct
	200	3000	1.34	.91 indirect combining (2)-(3)-(4)-(5)-(6)-(7)-(8)

Weighting the observations equally, we plot in Fig. 5 the averages of all. For each comparison four circles, each the average of 20 settings, represent the observations by the men; four crosses, those by the women.

It is apparent that the averages fit logarithmic straight lines closely and that there is no certain difference between circles and crosses, except in the comparisons of 2,000 and 4,000 against 3,000. It is near these frequencies that resonance is to be expected. The canal and the ear cavity have been taken in the pressure computations as of the *average* length and volume; for this reason the circles and the crosses would fail to coincide at frequencies near resonance should there be between men and women a systematic difference in shape of ear cavity.

Table III. is a condensed tabulation of the results obtained. The separate comparisons have been reduced to 700 cycles as reference frequency.

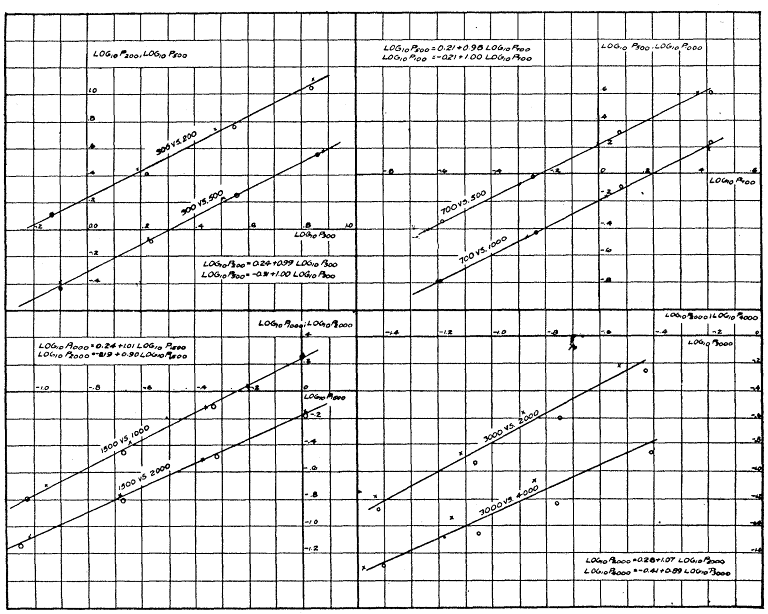

FIG.5 RESULTS OF THERMOPHONE COMPARISONS

Fig. 5.

Table III.

$\log_{10} P_f = A + B \log_{10} P_{700}$.

f.	*A.*	*B.*	Individual Extremes.	
			A.	*B.*
200.......	0.76	0.97	0.57, .96	0.62, 1.42
300.......	0.52	.98	.41, .65	.59, 1.18
500.......	0.21	.98	.14, .33	.77, 1.10
700.......	0.00	1.00	— —	— —
1,000.......	−0.21	1.00	− .29, −.09	.83, 1.29
1,500.......	−0.45	.99	− .66, −.33	.80, 1.22
2,000.......	−0.60	.89	− .81, −.38	.62, 1.09
3,000.......	−0.82	.84	−1.40, −.50	.63, 1.14
4,000.......	−1.14	.74	−1.67, −.79	.39, 1.37

RELATIVE SENSITIVITY OF THE EAR.

It is convenient to regard the data, taken all together, as yielding a determination of the acoustic pressures which phonometrically balance the pressure of 1 dyne per sq. cm. at 700 cycles. The reciprocals of these pressures express the relative ear sensitivity. The frequency of 700 cycles is chosen as standard because it is the last audible frequency in the average voice progressively attenuated, and the reference value of pressure roughly corresponds to the band of average speech between 600 and 800 cycles.

In Fig. 6, curve A is the ear *sensitivity* referred to the standard just described. The ordinates of this curve are the negatives of the values of A in Table III.; frequencies on the musical scale are plotted as abscissæ.

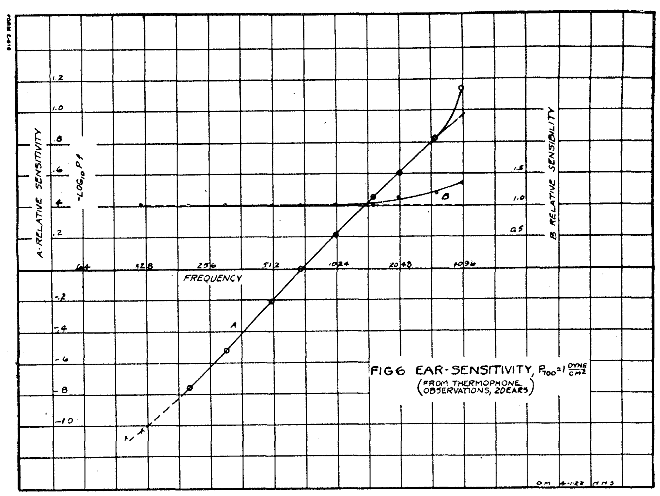

Fig. 6.

Values of B in Table III. show the change in log P_f required to maintain the phonometric balance when log P_{700} changes by unity. Reciprocals of the B's therefore exhibit the ear *sensibility* referred to 700 cycles: curve B, Fig. 6.

It is to be emphasized that the alternating pressures generated by the thermophone are obtained from computation. As yet no method has been devised for the immediate measurement of pressures on the ear drum, or for studying the reaction of the air chamber and walls of the ear on the thermophone. Until such ideal measurement is possible, the values of A cannot be guaranteed free from systematic errors. Probably these errors are small, and below 2,000 cycles do not greatly vary with frequency. The abrupt turn in curve A, Fig. 6, may be due either to resonance of the air cavity or to resonance of the drum.

The value of B, on the other hand, should be unaffected by an uncertainty in that of A, provided only the acoustic output of the sound generator be proportional to the electrical input. It will be noted that up to 1,500 cycles, the relative *sensibility* is unity, but increases appreciably to 1.35 at 4,000 cycles. Reëxamination of the data discloses the fact that if we exclude those observers whose comparisons above 1,000 cycles were in any case erratic, we have left eight ears out of twenty for which the values of B lie between 0.9 and 1.1. The indirect comparison of 4,000 and 700 involves five steps: blunders or errors in any one of these distort the series of B's for the ear concerned. It appears reasonable, therefore, to take the sensibility as uniform over the frequency range covered.[1]

In Fig. 6 observations at 100 cycles by 8 men and at 120 cycles by the 10 women are represented by crosses, to which the curve A is tentatively extended.

The advantages of the thermophone as a sound generator are convenience of computation and practical absence of transients. A serious disadvantage is the narrowness of the available range of loudness. The extremes of pressure within which the ear can accommodate are in the ratio 10^6 to 1; the thermophone surveys cover only one-sixth of this range, the pressure limits being 10 to 1. Conceivably, the simple law valid within these limits may fail outside them.

EXTENSION OF LOUDNESS RANGE.

Wider limits were reached by the use of an air-damped electromagnetic receiver in place of the thermophone. The supply circuit of the receiver includes an attenuator, as shown in Fig. 2. The dial of the attenuator is marked in "napiers": the introduction of N napiers reduces the voltage at the receiver terminals to e^{-N} times its former value. On this account it is convenient to express the sound output of the receiver in napiers (natural logarithms of the pressures).

The unattenuated sound emitted by the receiver is as loud as the ear can tolerate without discomfort. With the attenuator the tone can be reduced to inaudibility.

The electromagnetic receiver is calibrated in terms of acoustic pressure per volt input at the frequencies selected for the phonometer comparisons.

[1] This conclusion is confirmed by V. O. Knudsen, who finds the sensibility nearly independent of the frequency between 100 and 4,000 cycles: "Sensibility of the Ear to Small Differences in Intensity and Frequency" (abstract), PHYS. REV., 19, p. 261, Mar., 1922.

An "artificial ear," coupling the receiver and an electrostatic transmitter-amplifier system, enables the calibration to be made as follows:

An alternating voltage of a given frequency and appropriate magnitude is impressed on the receiver terminals and the corresponding amplifier output noted. The receiver is then silenced and a known voltage of the same frequency introduced into the amplifier input in series with the electrostatic transmitter. Comparison of the amplifier output in this case with that due to sound pressure on the transmitter diaphragm, together with the dynamical characteristic of the transmitter, permits computation of the sound pressure corresponding to the alternating voltage on the receiver. The artificial ear is intended to simulate the real ear in respect to volume and mechanical reaction on the receiver diaphragm. Were this simulation perfect, the observations just described would enable us to compute the pressures on the ear-drum when the receiver is held against the ear.

However, the simulation is far from perfect. The real ear affects the motion of the receiver in a way which the artificial ear imitates fairly well over the central region of the frequency range. But the cylindrical cavity and the rigid walls of the artificial ear differ greatly from the comparatively soft walls of the curved auditory canal and external ear, and the artificial ear fails at high and at low frequencies.

We have, then, a calibration of the electromagnetic receiver under conditions which differ from those of use, and the results of work with such a sound generator can not be stated in ideally accurate numerical values.

It is, however, permissible to use the receiver without the perfect calibration. Provided the pressure output of the receiver is proportional to the voltage at its terminals, and provided further that this voltage is known, it is possible to study variations in relative sensitivity as the loudness varies between wide limits.

Both requirements mentioned above may be incompletely satisfied. At high levels the receiver may be overloaded and the sound output cease to be proportional to the voltage. At low levels, where great attenuation is introduced, the impedance of parasite current paths may no longer be large in comparison with that of the network in the attenuator and the voltage at the receiver terminals may be incorrectly deduced from the dial setting. Such parasite paths are offered by capacity between input and output, due to conductors in the vicinity of the attenuator, and by induction owing to inadequate shielding of input and output leads. Care was taken to place and shield the leads safely, but it was desirable to determine how successfully this was done.

The proportionality of sound output to impressed voltage is tested by bringing the receiver up to the transmitter-amplifier and reading amplifier output currents for alternating voltages corresponding to attenuator settings from 0 to 4 napiers. As in the calibration of the receiver, voltages in the transmitter are determined. By reason of the great stiffness and small motion of the transmitter diaphragm, it is proper to assume proportionality of acoustic pressure and voltage generated in the transmitter. It is clear that the load characteristic of the receiver can be derived.

It was found that a correction on this account was not required above 200 cycles. The amplitude of the receiver diaphragm is greatest, and so overloading most easy, at the low frequencies. In the curves later shown the correction at 200 has been applied.

Parasite current paths, the existence of which leads to incorrect estimates of receiver voltage, are important only at low levels. Let the current input to the attenuator be the maximum permissible, and let N_1 be the dial setting necessary to reduce the sound output to the threshold. Now let the input current be reduced in the ratio $1 : e$; N_2 is the new threshold setting. When the parasite paths are negligible, $N_1 - N_2 = 1.0$. The threshold for any individual ear varies from day to day, but is sensibly constant over the few minutes required for this test.

Such an examination failed (for any of the frequencies here considered) to indicate errors exceeding a tenth of a napier,—an admissible experimental error.

Phonometric Comparisons with Electromagnetic Receiver.

Following these studies of the receiver, phonometric comparisons were undertaken by four observers. These comparisons with the electromagnetic receiver extended from 1 or 2 to 10 napiers above the threshold, taking 700 cycles as the reference tone. Each of the other tones was compared directly with 700, avoiding the objectionable features of indirect comparisons.

Before presenting the results obtained, it is profitable to consider what types of curves are to be expected in ideal phonometric comparisons covering a wide range of loudness.

Fig. 7, *I*, shows hypothetical Fechner curves, relating stimulus and "sensation," for the frequencies f_1 and f_2. Such curves for the ear have not yet been determined by experiment, but in drawing the hypothetical figures analogy between eye and ear has been presupposed.

Fechner curves for vision are constructed by integrating curves of sensibility (reciprocal of least perceptible stimulus increment) *vs.* logarithm of stimulus. Each curve contains (1) a curved portion at low intensities, concave toward the axis of sensation; (2) a straight portion, throughout which the least perceptible stimulus increment is constant; (3) another curved portion at high levels, concave toward the axis of log stimulus. At each end of the straight portion the curve bends because the least perceptible stimulus increment is no longer constant. Implicit in the construction of these curves is the assumption that whatever be the least perceptible change in the stimulus the accompanying change in the sensation is of invariable amount.

The sensation scale is undetermined, but we can imagine that by an ideal loudness balance, say at the level "*a*," coincidence of the scales for f_1 and f_2 has been established.

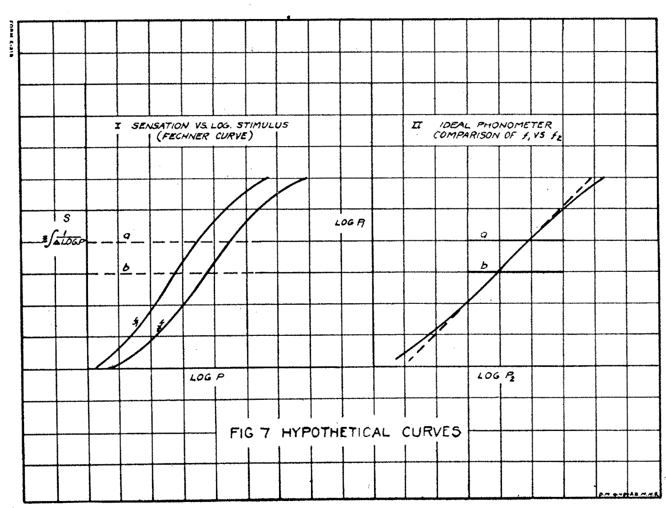

Fig. 7.

If phonometric comparisons are made of the tones represented by these curves, we shall obtain pairs of values of log P_1 and log P_2,—each pair will correspond to a definite sensation level, say "*a*" or "*b*." Fig. 7, *II*, shows, in the full line, the ideal phonometer results. In the figure to the left, the curves for f_1 and f_2 start from different thresholds and have different curvatures in the upper and lower portions. Centrally, where each curve is straight, phonometric comparisons will give a straight line for log P_1 *vs.* log P_2. If the slopes of the straight-line portions are the same, the slope of the phonometric line will be unity within these limits. At levels of loudness above "*a*" or below "*b*" however, the phonometric line will be curved as drawn. Were the sensation-stimulus curves at all ordinates uniformly spaced in abscissae, the phonometer would give the dotted line at 45°, coincident in the middle of the range with the full line.

Individual ears may be expected to vary in several respects. The threshold values of stimulus intensity vary with frequency for a given observer, and at each frequency differ with different ears. The values of stimulus intensity at which the Fechner curves become straight lines, and the stimulus intervals within which the lines remain straight, vary among frequencies for each observer and among observers for each frequency. Moreover, the characteristics of the ear change from day to day.

From the foregoing discussion, it is clear that we may expect two types of phonometric curves, provided the analogy holds between the eye and the ear. The types are (1) straight lines over a considerable range; (2) sharply curved lines of which the upper and lower halves are of opposite curvature. Lines of intermediate shapes will of course occur.

The observers who took part in the studies with the electromagnetic receiver are too few in number to make us sure that individual pecularities will be masked in the final average. Besides, the observing program covered six or eight hours for each ear (as against two or three hours in the thermophone surveys) and in three cases the observer was prevented from completing the program the same day he began it. It is therefore desirable to discuss the comparisons separately.

On examination, it was found that the observer who concluded the program in a single day obtained, for all comparisons, sensibly straight lines over the entire range. The three other observers obtained straight lines in most comparisons, but also a number of sharply curved lines of the second type anticipated above.

The distribution of these types and the general aspect of the data may be seen from Table IV. in which are tabulated the frequencies (each compared directly with 700 cycles) and the corresponding numbers of lines of each type.

Table IV.

f.	Sensibly Straight.	Sharply Curved.
200	4	0
300	3	1
500	4	0
1,000	2	2
1,500	2	2
2,000	4	0
3,000	3	1
4,000	3	1
	25	7

The preponderance of straight lines is unmistakable. In Fig. 8, at the left, the sensibly straight lines for each frequency are consolidated into an average line; at the right are drawn the individual curves which conspicuously depart from straightness.

Threshold settings were made for each frequency. These are plotted in Fig. 8 and the phonometer curves extended to them. The curves suggest that the auditory accommodation taking place in the comparisons is the same as at the threshold.[1]

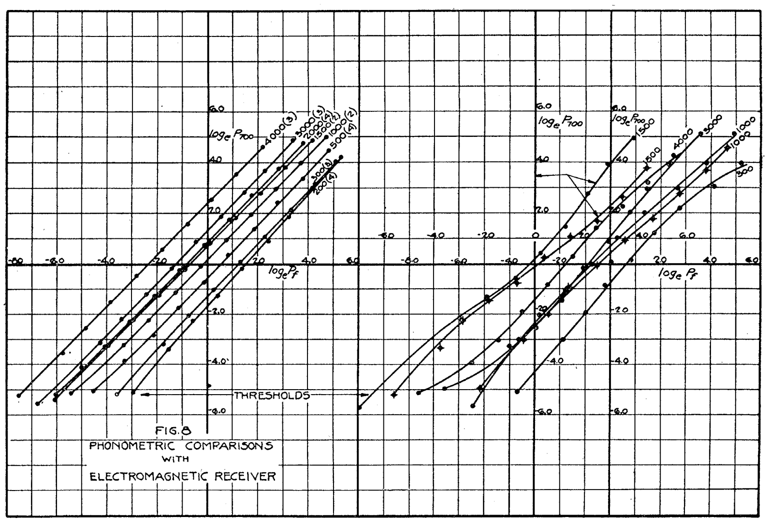

Fig. 8.

A short study was made by one observer, making on different days repeated comparisons of the same two tones. As might be expected, it was found that the curve obtained varied from straight on one day to curved on the next.

Care was taken by two observers to make a partial check of the validity of the phonometric technique by comparing two sounds of the same frequency (700 cycles). Whatever the calibration of the apparatus, equality of loudness in this case should mean equality of currents through the two contacts of the commutating relay. The greatest deviation from equality was 10 per cent. This occurred at the highest level; at intermediate and low levels the deviations were too small to be detected.

[1] The threshold sensitivity derived from these settings differs only at 3,000 and 4,000 cycles from that given by Fletcher and Wegel ("The Frequency-Sensitivity of Normal Ears," Proc. Nat. Acad. Sci., 8, 1, pp. 5–6, January, 1922). The discrepancy is no greater than the uncertainty of the receiver calibration, ascribed to resonance in the ear near these frequencies.

Relative Ear Sensitivity at Different Levels of Loudness.

Without regard to shapes of individual curves, we plot the average curve of each comparison and scale off at various levels of the 700-cycle tone the values of log P for the other frequencies. Doing this at three levels ($\log_e P_{700} = -4.0$, 0.0, and $+4.0$) we plot the values of $\log_e P_f$ with reversed signs and so draw at each level a curve of relative sensitivity of the ear. These are exhibited in Fig. 9, where, as in Fig. 6, the abscissae are frequencies on the musical scale; the ordinates, $-\log_e P$, are indicative of the relative sensitivity.

Obviously, the defects of the receiver calibration affect all these curves in the same way. The straightness of most of the curves shown in Fig. 8, and the closeness of their slopes to unity, insure the parallelism of the curves of Fig. 9.

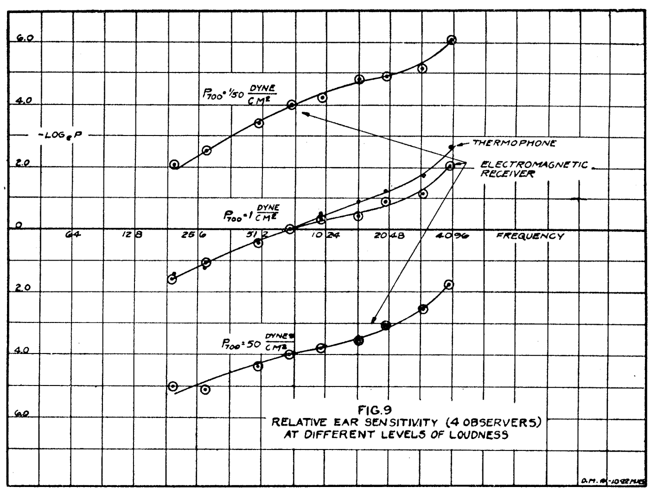

Fig. 9.

The calibration of the receiver and the computation of the thermophone output are both affected by unknown systematic errors. Numerous attempts were made to devise a method of comparing on the ear the sound output of the thermophone with that of the electromagnetic receiver. None of these attempts succeeded. Either the two sound generators must be interchanged on the ear or another receiver must be actuated by them alternately through the transmitter-amplifier system. In the first case it is impossible to make satisfactory comparisons, while in the second case the coupling to the transmitter sustains the uncertainty which the comparison is intended to remove.

As previously explained, the slopes of the lines should be unaffected by errors in the adopted sound pressure-frequency characteristic of either the thermophone or the electromagnetic receiver. From this point of view the two instruments agree: for the four observers using both, slopes by the thermophone over the central portion of the loudness range are 0.9 to 1.0; by the electromagnetic receiver, 0.9 at 200 *vs.* 700, 1.0 elsewhere.

SUMMARY.

1. At an intermediate level of loudness determinations with the thermophone have been made, by 20 observers, of the pressures of certain selected frequencies when these seem to the ear equally loud. The agreement among different ears is so close that improvement in the curve of relative sensitivity shown in Fig. 6 is to be looked for rather from verification of the pressure computations than from extending the survey to include a larger number of observers.

2. A limited number of observers have made observations over a range of loudness from 1 to 10 napiers above the threshold, using an electromagnetic receiver in place of the thermophone as source of sound. Their results are in general agreement with those obtained in the thermophone work, and strongly suggest that the relative ear sensitivity is invariable over this range.

3. The phonometric comparisons have been shown to be in harmony with Fechner's law, the application of this law to the ear being presumed valid.

4. The optical phenomenon known as the Purkinje effect has no analogue within the range of the phonometric comparisons. It is of great interest to continue this work at low intensities. In the present study, room noises made it impossible to work at levels near the threshold, where the Purkinje effect is perhaps to be found.

In conclusion, the results believed to have been accomplished may be thus stated:

I. A phonometer has been devised which permits accurate comparisons of the loudness of pure tones of different pitch.

II. With this instrument, evidence has been found that the relative sensitivity of the ear is independent of the loudness level over a wide range.

RESEARCH LABORATORIES OF THE AMERICAN TELEPHONE AND TELEGRAPH COMPANY,
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