THE AUDITORY MASKING OF ONE PURE TONE BY ANOTHER AND ITS PROBABLE RELATION TO THE DYNAMICS OF THE INNER EAR

By R. L. Wegel and C. E. Lane

Abstract

Auditory masking of one pure tone by another.—Using an air damped telephone receiver supplied with current with a proper combination of two frequencies, as source, the amount of masking by tones of frequency 200 to 3500 was determined for frequencies from 150 to 5000 per sec. The magnitude of a tone is taken as the logarithm of the ratio of its pressure to the threshold value, and masking is taken as the logarithm of its threshold value with masking to that without. The curves of masking as function of magnitude are approximated straight lines as a rule except for rounded feet, of slope s intersecting the magnitude axis at minimum masking magnitude m. For a given masking frequency n the slope increases from zero through nearly 1.0 for a frequency near n, then more slowly, approaching about 3 to 4 for the highest frequencies measured. The intercept is small or zero below n, then increases rapidly, approaching the value 3 for high frequencies. Except when the frequencies are so close together as to produce beats, the masking is greatest for tones nearly alike. When the masking tone is loud it masks tones of higher frequency better than those of frequency lower than itself. When the masking tone is weak, there is little difference. If the masking tone is introduced into the opposite ear, no appreciable masking occurs until the intensity is sufficient to reach the listening ear through the bones of the head. At intensities considerably above minimum audibility, there is no longer a linear relation between the sound pressure and the response of the ear. Data are given showing *combinational tones* resulting from this non-linearity when two tones are simultaneously introduced in the ear. The presence also of *subjective overtones* in a loud tone accounts for the large amount of masking of tones higher than itself by a loud masking tone.

Dynamics of inner ear.—The data on masking together with Knudson's data on frequency sensibility are interpreted in terms of the *dynamical theory of the cochlea* which ascribes its frequency selectivity to a passing of vibrations along the basilar membrane and a shunting through narrow regions of the membrane at points depending on the frequency. Conjectured curves are given for a few single frequencies of the amplitude of vibration of this membrane as a function of the distance along it.

Part I. Auditory Masking of One Pure Tone by Another

1. Introduction

In past work on audition very little attention has been given to the phenomenon of masking. A. M. Mayer[1] has left a more complete record of observations on masking than any one else. He concludes that

[1] Mayer, Phil. Mag. **11**, 500, 1876

low frequency sounds may completely "obliterate" higher frequencies of considerable intensity but higher frequencies do not "obliterate" lower ones. In his experiments he used organ pipes for low frequencies and tuning forks for the high ones. With the organ pipe sounding, the action of the fork could be made intermittent by moving the hand to and fro over the mouth of a resonance box with which it was used. He describes his results in part as follows: "As the vibrations of the fork run down in amplitude, the sensations of its effect become less and less until they soon entirely vanish. Indeed the vibrations of the forks may be suddenly and totally stopped without the ear being able to detect the fact. But if instead of stopping the fork when it becomes inaudible, we stop the sound of the organ-pipe, it is impossible not to feel surprised at the strong sound of the fork which the open pipe had smothered and had rendered powerless to affect the ear. No sound, even when very intense, can diminish or obliterate the sensation of a concurrent sound which is lower in pitch. This was proved by experiments similar to the last, but differing in having the more intense sound higher (instead of lower) in pitch."

The experiments of Mayer are of course only qualitative. The work described in this paper was undertaken to obtain quantitative data and to find an explanation for the phenomena observed.

2. *Definition of masking.* Unless otherwise specified, whenever the term masking is used, it is intended to mean the masking of one tone by another when both are introduced in the same ear. For convenience in presenting data, the magnitude of a tone is defined as the ratio of its pressure to that of its minimum audible value. A logarithmic scale is used in plotting. If a minimum audible pressure of one tone is p_1 and the introduction of a second tone changes its minimum detectable value to p_2, the ratio p_2/p_1 is taken as the magnitude of the masking of the first tone by the second and is likewise plotted on a logarithmic scale. In this paper the term pressure is used to signify the root mean square value of the sound pressure in the external ear passage.

3. *Range of intensities and frequencies of the tones used.* Fig. 1 is a diagram of the auditory sensation area.[2] This figure practically describes itself. It shows that the region of sensation covered by these experiments includes the most important range of frequencies and intensities. The higher levels in this region near the threshold of feeling are generally impracticable for extended experimentation because they induce tinnitus. The very low and very high frequencies are not covered in this work because they are of lesser importance, and furthermore, intense and

[2] See Wegel, Proc. Nat. Acad. Sci., July, 1922 and Bell System Tech. J., Nov. 1922.

pure tones at low frequencies and intense tones at high frequencies are produced with difficulty.

4. *Masking as a function of intensity.* Fig. 2 shows the amount of masking of various frequencies from 250 to 4,000 cycles produced by an 800 cycle tone, plotted as a function of the magnitude of this masking tone. For example, the first curve shows the amount of masking, as already defined, of 250 cycles plotted as a function of the magnitude of an 800 cycle masking tone. Each plotted point represents the average of

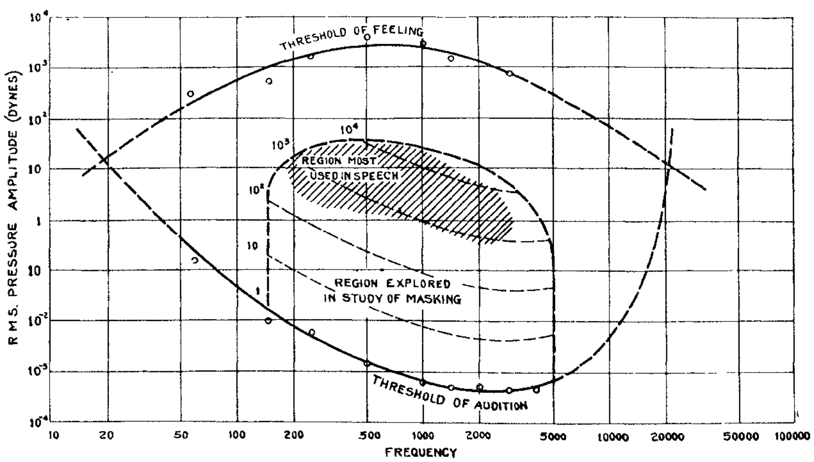

Fig. 1. Auditory sensation area.

four observations taken in succession at one time. In all figures the masking tone is designated by F_1 and the masked by F_2. These curves were all obtained for one observer except the dash-dot ones, which are included here to show the small amount of variation usually found when taking masking data for different observers of normal hearing.

The curves do not all pass through the origin as they evidently should except, as will be explained later, when the tones produce beats. The minimum audible reference value used was the average taken over a period of several days. Plotted in this way it was found that such curves varied from day to day near minimum audibility but for the higher intensities checked within the experimental error. The general magnitude of the deviation of the lower end of the curve from the origin will be seen from the variations shown by the curves. This shows that the ear is quite variable in its behavior near minimum audibility, but comparatively constant for louder tones. The curves as corrected by the dotted lines represent a close approximation, in each case, to the average curve which would have been obtained if the observations had extended over a long period of time. This correction does not apply when the tones produce beats.

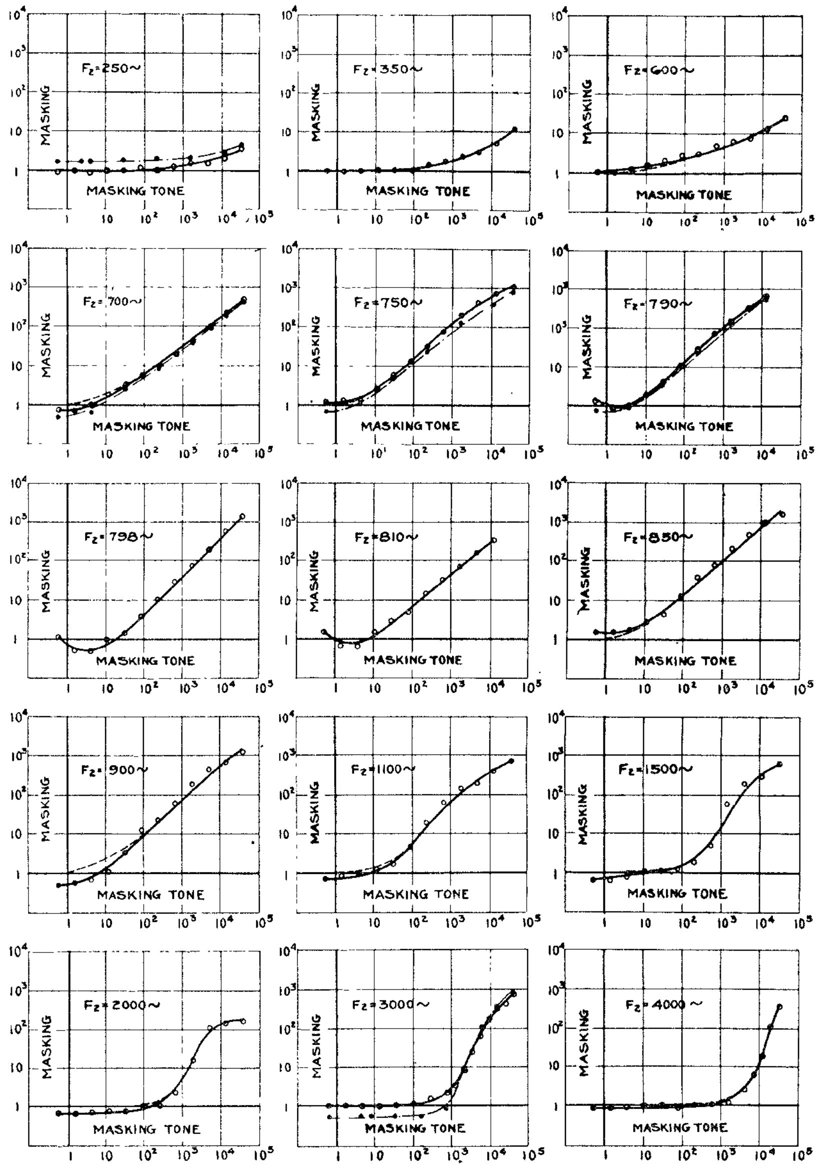

Fig. 2. Data for masking tone of 800 cycles.

Fig. 3 shows some of the corrected curves from Fig. 2 reproduced on common axes. Curves for masking tones of 200, 300, 400, 600, 1200, 1800, 2400 and 3500 cycles are also included in this figure. The frequency of the masked tone is indicated on each curve.

From the figures certain general facts are evident. A tone of a frequency much below the masking tone is not perceptibly masked for the lower range of intensities and hardly more than perceptibly so when the tones are very loud. A tone of much higher frequency than the masking

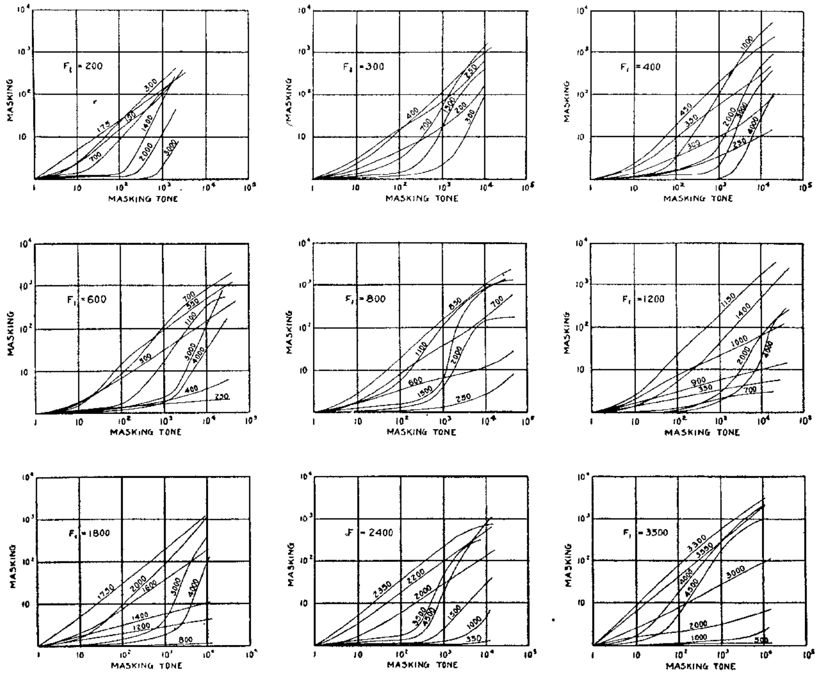

Fig. 3. Masking for tones in same ear.

tone is not perceptibly masked for the lower range of intensities, but at a rather definite high intensity masking occurs perceptibly and quickly becomes very great as the masking tone is increased. In general, masking is greater when the tones lie close together, the curves approaching straight lines with 45° slopes, intercepting the axis of abscissas at about ten times the minimum audible pressure of the masking tone.

When the tones are close enough together in frequency to beat, they do not give masking curves in the same sense as when farther apart. They represent measurements of the minimum perceptible fluctuation of the beating tone. Two such tones, separately inaudible, but each not lower than one-half the minimum audible pressure, will obviously beat when introduced together in such a way as to be alternately audible and inaudible. This effect accounts for the depression in the curve at low intensities in Fig. 2 for $F_2=790$, 789 and 810. At higher intensities the magnitude of the minimum perceptible beating fluctuation may be obtained from the difference between abscissas and ordinates. The minimum detectable amount of this fluctuation has been found to decrease as the beat frequency decreases, approaching a value which would be expected from ear sensibility data.

The sudden increase in slope of the curves when the masked frequency is higher than the masking frequency is associated with the appearance of combinational tones. The curve in Fig. 2 for $F_2=2000$ shows a decided bending over at high intensities. This and similar bendings may be accounted for on the supposition that both tones are conducted through the head to the opposite ear in such relative amounts that the masked tone is detected there while it is still masked in the ear to which the sound is applied. It has been found that a small amount of bone conduction takes place between the receiver ear cap and the mastoid bone. The phenomena of combinational tones and head conduction will be discussed later.

5. *Masking as a function of frequency*. Fig. 4 shows the masking of tones of various frequencies by a masking tone of 1200 cycles at 160, 1000 and 10,000 times its minimum audible value. With the exception of

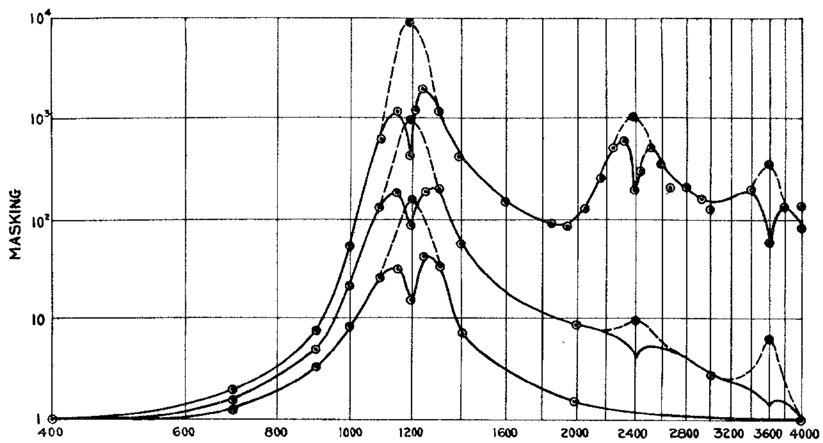

Fig. 4. Masking of various frequencies by 1200 cycles.

the region near the masking frequency where beats occur, the lowest curve shows a gradual falling off of masking as the masked frequency departs on either side from the masking frequency. Within the region of beats, the amount of masking decreases as the masking frequency is approached. The intersection of the curves at the masking frequency may be interpreted to give intensity sensibility. The highest curve differs in that its characteristics in the region of the first and second overtones of the masking frequency are much like those in the neighborhood of the masking frequency. It resembles such a curve as might be expected from a knowledge of the lowest curve if three masking frequencies, 1200, 2400 and 3600 cycles were present, with relative magnitudes of 1:0.1:0.025. An harmonic analysis of the sound as picked up by a condenser transmitter, showed that these tones were not appreciably present in the air. These and other tests were made, in fact, in all measurements recorded in this paper, and in no case was the distortion in the receiver detectable. Since beats are obtained at the frequencies of overtones, it is concluded that these harmonics are introduced subjectively in the ear due to some non-linear characteristic of its response. The magnitude of these overtones may be obtained experimentally by increasing the intensity of a secondary tone of such a frequency as to beat with the harmonic, to a point where beats are most prominent and taking the intensity of this

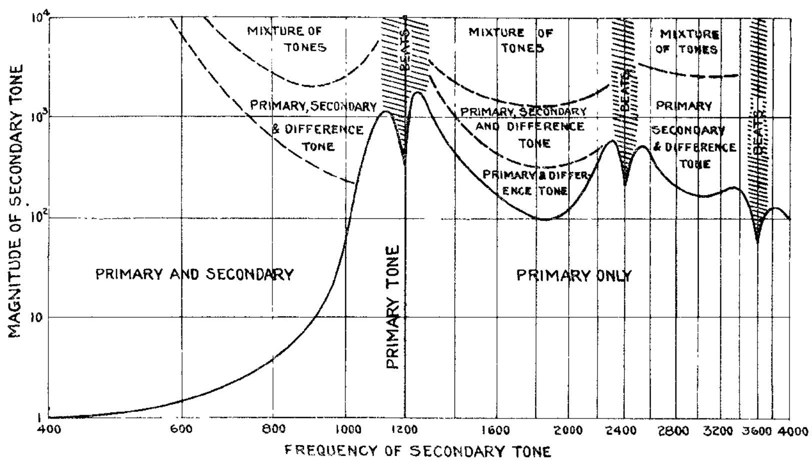

Fig. 5. Sensation caused by two pure tones.

tone to be equal to the intensity of the overtone. The dots represent the magnitudes of the harmonics so determined. This method is not very accurate because the intensity of the variable tone at which the most prominent beats are heard tends to be somewhat higher than the fixed overtone. The middle curve represents a transition between the other two. It indicates harmonic components of relative magnitudes 1:.01:.006. These curves show that a tone masks frequencies higher than itself better than lower frequencies only when it is loud.

6. *Non-linearity of response of the ear.* The character of the sensation, when two tones are acting together on the ear, varies considerably with the relative frequency and intensity values. Fig. 5 represents the sensa-

tion caused by a tone of fixed frequency, 1200 cycles, and magnitude 10^4, in combination with various secondary tones of which the frequencies are represented by the abscissas and the magnitudes by the ordinates. The continuous curve is the same as the top curve in Fig. 11. The various areas represent ranges of magnitude and frequency of the secondary tone in which combinational tones of various kinds, as indicated, appear. As any secondary tone of a frequency below about 1000 cycles, for example 800, is gradually brought up in intensity from a sub-audible value to a point at which it is just detectable, it is first heard as a separate tone along with the primary tone. In the lower part of this range, the intensity of the secondary tone may be increased to very large values and still be perceived independently of the primary. When, however, the intensity of the secondary tone is increased to a point indicated by the dotted line, the difference tone is distinguishable and increases gradually in relative intensity as the area above this line is crossed. At the high intensities in this region, a very complex mixture of tones is heard. When a secondary tone of 1900 cycles is introduced in the same way, its presence is first detected by a difference tone, and the secondary is not heard. As the intensity is further increased, the secondary tone becomes audible along with the difference tone. As the intensity is increased to the higher levels, the mixture of tones becomes more and more complex. With this explanation, the meaning of the rest of the figure will be obvious.

A careful analysis was made of the mixture of tones present in the ear when a primary of 1200 at a magnitude 6×10^4 was present along with a secondary of frequency 700, of about the same intensity. The component frequencies were determined by introducing a third tone of known variable frequency and determining the frequencies at which beats occur. If f_1 represents the primary, and f_2, the secondary, the frequencies found in the mixture were f_1, 1200 cycles; f_2, 700; f_1+f_2, 1900; f_1-f_2, 500; $2f_1$, 2400; $2f_2$, 1400; $3f_1$, 3600; $3f_2$, 2100; $2f_1+f_2$, 3100; $2f_1-f_2$, 1700; $2f_2+f_1$, 2600; $2f_2-f_1$, 200 (?); $4f_2$, 2800; $2f_1+2f_2$, 3800; $2f_1-2f_2$, 1000; $3f_1+f_2$, 4300; $3f_1-f_2$, 2900; $3f_2+f_1$, 3300; $3f_2-f_1$, 900. No attempt was made to determine their magnitudes although this can probably be done approximately by measuring the intensity of the exploring tone at which the beats at each frequency are most prominent. With the exception of the frequency $4f_1$, this series is all that would be expected if the response of the ear were non-linear and represented by the equation:

$$x=a_0+a_1p+a_2p^2+a_3p^3+a_4p^4.$$

In this equation, x is the response of the mechanism of the middle ear; a_0, a_1, a_2, etc., are constants, and p is the pressure in the ear canal. While frequencies introduced by higher powers of the pressure were probably present, they were very faint and no careful search was made for them. No careful investigation has yet been made of this phase of audition. Results of further work may call for modifications of the interpretation

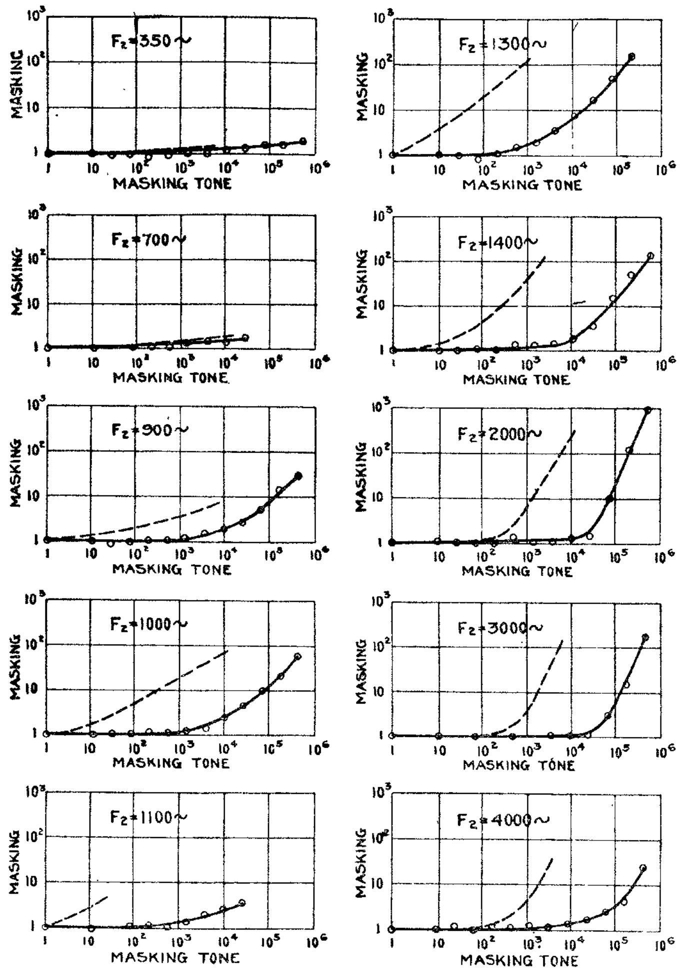

Fig. 6. Masking data for tones in opposite ears, masking tone 1200 cycles.

given here. It may be interesting to note in this connection that one of the striking characteristics of some kinds of abnormal hearing has been found[2] to be an exaggerated departure from linearity.

7. *Masking with tones in opposite ears.* Fig. 6 gives the masking when the masked and masking tones are introduced in opposite ears. The dotted curves show the corresponding data for tones in the same ear. The two sets of curves are nearly alike except for displacement in the

ratio of $1:10^2$ to $1:10^3$ along the horizontal axis. These curves may be explained by assuming that there are two kinds of masking, central and peripheral, the former being generally relatively small and resulting from the conflict of sensations in the brain and the latter originating from overlapping of stimuli in the end organ. Central masking is probably always present to a certain extent whereas peripheral masking can only occur when the two tones excite the same region on the basilar membrane. All large amounts of masking may be attributed to peripheral masking. The similarity, except for the displacement already noted, of the two sets of masking curves indicates that most of the masking for loud tones in opposite ears is peripheral masking, caused by the conduction of the masking tone through the head to the opposite ear with sufficient intensity to cause peripheral masking there. This presumes an attenuation of the tone through the head from one ear to the other of the same order of magnitude as the displacement between the two sets of masking curves.

The magnitude of the masking tone in these experiments was referred to the minimum audible value for the ear into which it was introduced. The magnitude of the masking was referred to the minimum audible value for the opposite ear. It will be seen, therefore, according to the explanation offered above, that the amount of displacement of a curve gives the sum of the conduction loss through the head and the difference in sensitivity of the two ears. If both had been referred to the minimum audible value of the ear receiving the masked tone, the displacement would have given the attenuation through the head. Since the two ears of the observer did not differ greatly in sensitivity, this displacement gives the proper order of magnitude for the attenuation.

There is still further evidence that when a tone is introduced into one ear by a telephone receiver, the opposite ear is also excited but to a lesser degree. Cases of persons very deaf in one ear have been noted for which 10^2 to 10^3 times the current is required for audition with the receiver on the deaf ear over that for the receiver on the good ear. Also, when the sound for the receiver on the deaf ear is audible, it may be greatly enhanced by placing the finger in the good ear, indicating that the sound is not only heard first in the good ear but that it arrives there by bone conduction. Furthermore when two tones of the proper frequencies to beat are introduced in opposite ears the best beats[3] are always heard when one of the tones is over 100 times the amplitude of the other and the relative intensities for hearing these best beats are nearly indepen-

[3] In this connection, see G. W. Stewart, Phys. Rev. **9**, 514, 1917. Stewart's conclusions are somewhat at variance with those arrived at here.

dent of the sensitivity of the ear to which the louder tone is applied. In fact this ear may be entirely deaf, or, if normal, its sensitivity may be lowered by plugging, and best beats will still be heard at the same relative currents through the receivers.

In view of the approximate agreement of all the evidence of head conduction, it seems safe to conclude that this phenomenon actually exists and that it accounts for the resemblance of the two sets of masking curves in Fig. 6. This attenuation through the head, of course, applies only when telephone receivers are used in the ordinary manner as the sound source. When other sources were used, different values of attenuation were found.

Part II. Dynamics of the Inner Ear

8. *Dynamical theory of the cochlea.* A consideration of the anatomy of the cochlea makes it unreasonable to suppose that the individual hair cells, basilar fibers or rods of corti can act as independent resonators, even assuming that dissipational impedance to their motion is small enough to permit of resonance. The motion of each must be greatly affected by the reactions of others due to their dynamical proximity. One element cannot resonate without setting the others in vibration and itself have a complex motion with component frequencies corresponding to all the modes of motion of the complete system which would be obtained by means of its Lagrange discriminant or the equivalent. These frequencies are not generally the resonance frequencies of the vibrating elements themselves. This sort of consideration leads to a treatment of the dynamics of the cochlea as a whole such as that explained by Roaf.[4]

The mechanism assumed here of the action of the cochlea may be explained by reference to Fig. 7a, which represents the cochlea uncoiled.[5] The stapes, in responding to the sound pressure received through the middle ear, is displaced in the oval window, causing a mass movement of the liquid in the scala vestibuli and scala tympani, which except for a small yielding of the labyrinthine walls, results in an equal and opposite displacement of the membrane of the round window. This mass movement of the liquid can take place only by means of the displacement of the basilar membrane or through the helicotrema. If the pressure change is very slow, the movement will take place through the helicotrema. If the pressure change is more rapid, i.e., if the frequency is increased, most of the movement will take place through the displacement of the

[4] Roaf, Phil. Mag., (V) **43**, 49, Feb. 1922

[5] Wrightson, The Analytical Mechanism of the Internal Ear

basilar membrane. This displacement will have a well defined maximum at some definite point, the location of which depends on the frequency, and will decrease rapidly on either side of this maximum. As the frequency is increased, the position of the maximum approaches the proximal end of the membrane.

The motion of the basilar membrane in any region may be assumed to produce a stimulus of the nerve terminals in that region. This stimulus

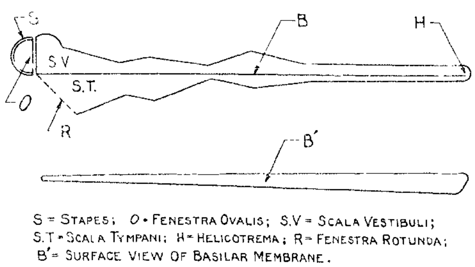

FIG. 7a. Cochlea uncoiled.

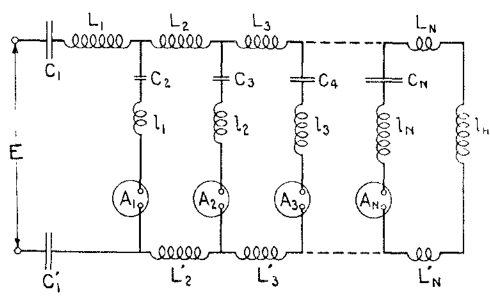

FIG. 7b. Electrical analogue of the cochlea.

may be due to the relative motion of the basilar and tectorial membranes, or flexure of the basilar membrane, or to both. In any case, the amount of the stimulus of any nerve terminal may be taken as a direct function of the motion of the membrane at the point at which it terminates.

A "lumped constant" electrical analogue of the cochlea is shown in Fig. 7b. Although the analogy is not very close, its selective characteristics are similar to those of the cochlea. The inductance L_1 corresponds to the mass of the stapes and its attached parts, C_1, the elasticity restraining its motion, C_1', the elasticity of the round window membrane. The inductances L_2, L_3, etc. represent elements of mass of the fluid in the scala vestibuli, L_2',L_3', etc. similar constants for the scala tympani; C_2, C_3, C_4, etc., the elasticities of elements of the basilar membrane; l_1, l_2, etc. their masses as augmented by contiguous elemental volumes of fluid on either side. A_1, A_2, A_3, etc. are ammeters corresponding to the nerve terminals on the various elements of the membrane. L_h

corresponds to the element of fluid mass in the helicotrema. The series inductances decrease essentially along the structure to correspond with the decreasing cross section of the two scala. The shunt inductances vary more or less in proportion to the widths of successive elements of the membrane. The capacities increase to correspond to the increasing flexibility of the membrane due to its increasing width. Neither the exact magnitudes and variations nor the exact dispositions of the elements of this analogue can be given because the dynamical constants of the parts of the cochlea are not known. Resistances are, of course, associated in various ways with the inductances and capacities. These are not represented in the figure. This electrical network should behave much like the cochlea in that, as the frequency increases, the meter giving a maximum reading is nearer and nearer the source.

9. *Positions on the basilar membrane of maximum response to various frequencies.* It is found that if the two points of a pair of dividers are brought in contact with the back of the hand, the minimum separation at which they can be distinguished separately is about 32 mm. On the finger tips where the nerve terminals are more numerous this distance is about 2.3 mm. According to the theory of the cochlea given above, two frequencies nearly alike cause maximum stimulations at adjacent points on the basilar membrane. The minimum detectable difference in frequency then corresponds to the minimum detectable distance between the corresponding maxima on the membrane. The auditory nerve terminals are quite evenly distributed along the membrane so that it may be assumed as a first approximation that the space interval between two disturbances which are just separately distinguishable is the same all along the membrane. This interval corresponds to the minimum detectable frequency difference, as given by sensibility data, between the tones causing the two disturbances. If f_1 and f_2 are the lower and higher limits to which the basilar membrane responds, l_0 the total length of the membrane, l the distance from the helicotrema to the point at which the disturbance corresponding to a frequency f takes place and Δf the minimum perceptible difference in frequency:

$$l\int_{f_1}^{f_2}\frac{df}{\Delta f} = l_0\int_{f_1}^{f}\frac{df}{\Delta f}$$

The distribution of frequency response along the membrane is plotted in Fig. 8. This was calculated from Knudsen's frequency sensibility data and using the frequency limits 0 and 15000 cycles and 31 mm for the length of the membrane. The sensibility at extremely high frequencies is so small that the value of f_2 may be anything from 10000 cycles to infinity without appreciably affecting the general distribution. Similarly

f_1 may be taken as any frequency from 0 to 50 cycles without materially affecting the distribution because this range is so small compared to the audible range of frequencies. The plot, Fig. 8, shows that 1000 cycles falls about at the middle of the membrane and that distances corresponding to equal frequency intervals decrease rapidly as the stapes end is approached.

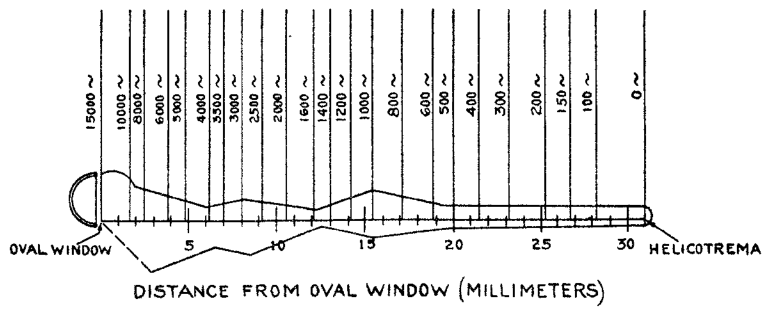

Fig. 8. Characteristic frequency regions on basilar membrane.

It is interesting to compare the space discrimination on the basilar membrane with those on the back of the hand (32mm) and finger tips (2.3 mm). The sensibility data interpreted as above give about .02 mm.

10. *Variation in amplitude of vibration along the basilar membrane for a single frequency.* Fig. 9 shows a hypothetical curve of the variation

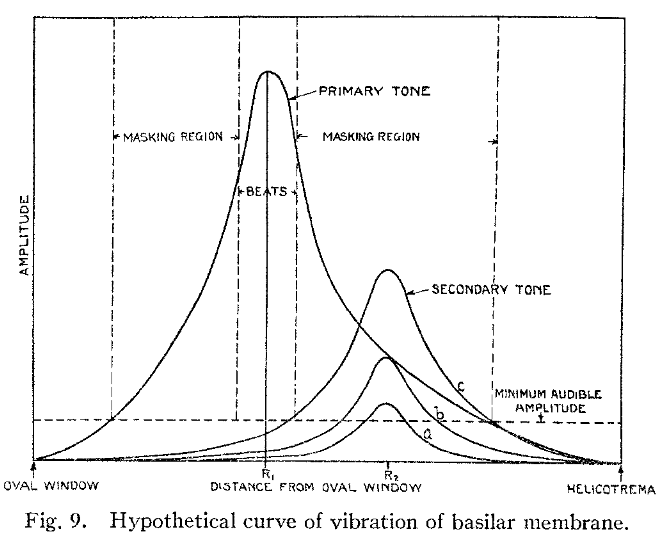

Fig. 9. Hypothetical curve of vibration of basilar membrane.

of the basilar membrane along its length, in response to a primary tone of single frequency. This curve has a maximum at a point in the region R_1, and falls off rapidly on both sides. A dotted line is drawn to show the minimum amount of vibration necessary to produce perceptible stimulation of the nerve terminals along the length. It may be assumed that the nerves are nearly enough alike, along the membrane, and similarly situated, so that the actual motion necessary to produce minimum audible sensation is about the same at all points. Three other curves corresponding to three different magnitudes of the secondary tone are also shown. These curves have maxima in the region R_2. Curve a corresponds to a stimulus which in the presence of the primary tone is not detectable, but alone is audible. Curve c corresponds to a stimulus which is detectable in the presence of the primary. Some magnitude between curves a and c must correspond to a minimum detectable magnitude of the secondary tone. This is a magnitude at which some definite relation exists between the amplitude caused by the secondary tone in the region R_2, and the amplitude at the same place caused by the primary tone. These amplitudes have been tentatively assumed equal in this work, that is, that the secondary tone, when just detectable, is represented by curve b. The acceptance of a ratio of different order of magnitude is unreasonable and a fine discrimination cannot be justified at this time. Fragmentary evidence, which will not be gone into here, indicates that the ratio should not differ greatly from unity. On this assumption, if central masking is neglected, a secondary tone may be used as an exploring stimulus to measure the amplitude of motion, due to a primary tone, of the basiliar membrane at various points along it except in remote regions where the amplitude is less than that necessary for sensation, and very near the maximum, where the primary and exploring tones beat.

The maximum amplitude on the membrane due to any single tone, in units of the minimum audible amplitude of the membrane, is its "magnitude" as already defined. The maximum value of the curve of a primary tone is therefore given by its magnitude. The amplitude of vibration at any point in regions where masking occurs is given by the magnitude of masking of the exploring or secondary tone.

11. *The curves of vibration of the basilar membrane at different frequencies.* Fig. 10 shows the vibration of the basilar membrane for different frequencies as determined from experimental data by the method described in the preceding section, for amplitudes corresponding to the same pressure of .5 dyne per cm^2 in the external ear canal. This corresponds to a sound which is not so loud as to produce noticeable harmonics. The dotted curve is the locus of the maxima for all frequencies at a constant pressure of .5 dyne in the external ear canal for the ear on which the measurement was made. This curve represents the average of data

taken over a long period of time so that irregularities which are usually present in a single curve are eliminated. The unit is as before the amplitude of the membrane necessary for minimum audibility but the scale is arithmetic. The curves become less sharp as the frequency is decreased. This is in agreement with what would be expected from the dynamical structure of the cochlea. At very low frequencies the stimulus may be conceived of as due to a more or less bodily motion of the tectorial membrane along the basilar membrane.

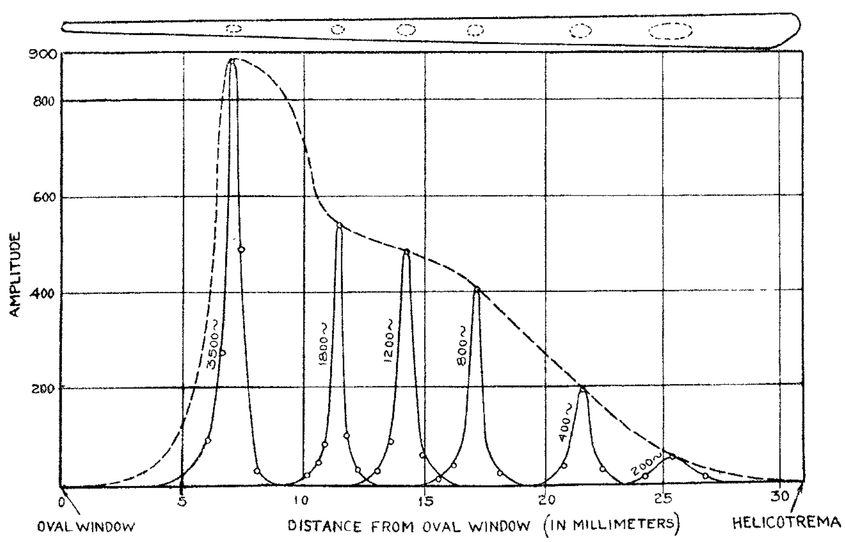

Fig. 10. Amplitude along basilar membrane for different frequencies; r. m. s. pressure 5 dynes.

It is to be expected that similar curves at extremely high frequencies should become less definite, probably not by becoming flatter, but by having their maxima at or beyond the proximal end of the organ of corti. This conclusion is arrived at principally from a consideration of the curves of absolute sensitivity of normal ears (see Fig. 1) in which the sensitivity is seen to drop off very sharply at about 15,000 cycles.[6] This sort of an assumption is further substantiated by the fact that when plotted as displacement of the basilar membrane, sensitivity curves of abnormal ears in which the lesion can be reasonably well traced to degeneration of the nerves of the proximal end of the basilar membrane, also indicate similar sharp cut-offs at frequencies much lower than 15,000 cycles whereas no such abrupt cut-offs of lower frequencies have yet been

[6] For original data see C. E. Lane, Phys. Rev. **19**, 492, May 1922

recorded.[7] According to this theory of the action of the cochlea, it follows that as long as there is sensitivity in any of the nerves, even if it is only in a small region, the ear will be able to detect any frequency if it is loud enough, and that it will detect with greatest sensitivity those frequencies for which the sensitive region is characteristic.

A plan view of the basilar membrane is shown drawn to scale, at the top of the figure. Conjectured contour lines are drawn enclosing areas over which the amplitude is more than one half that of their centers. The lengths of these areas are obtained from the curves shown in the figure and their widths by taking one half the width of the membrane.

Fig. 11 shows curves of response of the basilar membrane for two frequencies, 1200 and 3500, at constant amplitudes of the membrane of 8000 times the minimum audible amplitude. This, of course, did not represent equal pressures in the external ear canal. The secondary maxima caused

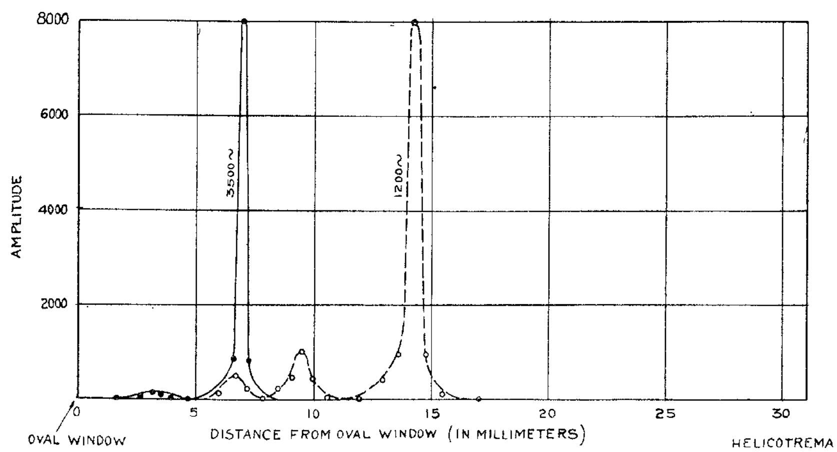

Fig. 11. Amplitude along basilar membrane for loud tones.

by the subjective overtones are present in each case. It seems most reasonable to ascribe the non-linearity producing these overtones to some part of the middle ear, possible the joint between the hammer and anvil which may have enough static friction to give a rubbing effect when vibrating violently.

The conjectured vibration of the membrane with two loud tones of 1200 and 700 cycles under conditions described in section 5 is qualitatively shown in Fig. 12. The vertical lines indicate the positions of maxima. Their magnitudes cannot be given at this time. This indicates that a

[7] For example, see E. P. Fowler and R. L. Wegel, Audiometric Methods and Their Application, Trans. Am. Laryngological, Rhinological and Otological Society, 1922.

large portion of the membrane responds to comparatively simple stimuli when they are loud.

12. *Discussion.* A tentative interpretation of the principal pertinent data available has been made in terms of the theory that the cochlea separates vibrations according to their frequencies, projecting them so to

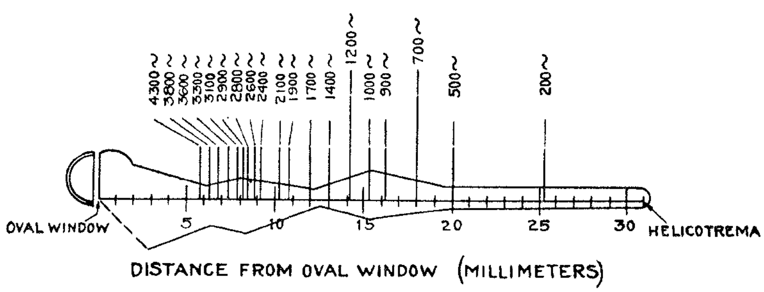

Fig. 12. Combinational tones.

speak, from the stapes through their various appropriate regions of the basilar membrane where they are sensed, and then passing them back to the round window where their pressures are relieved. While this interpretation is probably the simplest that could be made, and the present data seem to be in accord with it, it is of course, possible that other satisfactory interpretations might be found, though they are not very obvious. On account of the inaccessibility of the ear, the determination of its dynamics depends on indirect methods such as those in this paper. Many details as given here might with equal justification have been varied quantitatively to a certain extent. It is hardly worth while going into a further discussion of these details in view of the limited amount of applicable data upon which they depend.

It might be well to explain a little more in detail the general features of the mode of perception of relative pitch and intensities. The brain is assumed to detect differences in pitch simply by experience in associating the stimulation of different groups of nerves with different pitches. Differences in intensity may be detected either by the violence of agitation of nerve terminals at the position of its characteristic maximum or by bringing into play new terminals at the sides of the peak which at lower intensities are subject to subaudible stimulus or more likely both. It is often observed that a small change in intensity is mistaken for a change in frequency. This means that the brain can detect very small changes in position or altitude of the vibration curve of the basilar membrane, but cannot distinguish between these changes unless they exceed a certain definite amount.

The exact position of the maxima on the membrane must vary with intensity because of the varying effect of non-linearity. All curves given in this paper are located on the membrane by means of the sensibility curve at 100 times the minimum audible amplitude. The exact location of these maxima is also quantitatively uncertain as already stated because of a lack of the knowledge of distribution of sensory terminals on the membrane and the relation between this distribution and the minimum detectable distance between maxima. The frequency sensibility and the widths of the peaks of vibration might be expected to be related. The fragmentary data bearing on this point show no simple agreement but the frequency sensibility is the most logical to use at this time in determining the location of frequency response on the membrane.

Nothing has been said of the action of the apparatus of the middle ear. The data given here do not directly bear on that problem. If the minimum audible stimulating motion at all nerve terminals is the same, then the dotted curve of Fig. 10 obtained from minimum audibility gives the frequency characteristics of the combination of middle ear apparatus and cochlea. A determination of the mechanics of this combination or its elements will probably have to be done indirectly from this standpoint.*

Appendix: Apparatus and Method

The apparatus was essentially the same as previously used in this laboratory in the determination of the frequency-sensitivity of normal ears.[8] An air damped telephone receiver was used as the sound source. The currents at different frequencies were supplied by means of special vacuum tube oscillators equipped with filters to eliminate effects due to harmonics. Two voltage attenuators were used, one for the primary, and one for the secondary frequency. These attenuators were of the dial type reading voltage directly on a logarithmic scale and having a total range of 1 to 10^6. In taking data on masking for both tones in the same ear the output of the attenuators was connected in series with the receiver. In this way it was possible to vary the receiver voltage for each frequency independently. The minimum audible voltage for each frequency was separately determined, keeping the other considerably below minimum audibility. The primary voltage was then kept constant at different

* It should be obvious, contrary to an impression apparently created (J. P. Minton, Phys. Rev. **22,** 506, Nov. 1923) in the discussion of this subject at the April 1923 meeting of the Physical Society at Washington, that our assumptions attribute masking ultimately to an inability of the brain to perceive separately, two stimuli on the basilar membrane which are caused by motions of this membrane bearing the relations given in section 10 of this paper.

[8] Fletcher and Wegel, Phys. Rev. **19,** 553, June, 1922

levels above minimum audibility while the secondary was gradually brought up from below minimum audibility until its presence produced a just noticeable change in what was heard while listening to the primary. The ratio of the just detectable voltage of the secondary in the presence of the primary to the minimum audible voltage of the secondary was taken as the corresponding pressure ratio, hence the amount of masking as defined in Part I was found. The ratio of the primary voltage as used to its minimum audible voltage gave its magnitude. In the case of tones in opposite ears the procedure was nearly the same. Two receivers, one for each ear, were used in connection with separate attenuators. The primary tone in one ear was set at a definite magnitude above minimum audibility for that ear, and the amount of masking of the secondary tone in the opposite ear observed.

Research Laboratories of the
American Telephone and Telegraph Company
and Western Electric Company, Inc.,
July 23, 1923.