No. 134

THE INSTITUTION OF
POST OFFICE ELECTRICAL ENGINEERS

Sound and Hearing.

SOME PRACTICAL PROPERTIES OF THE SOUNDS TO WHICH WE LISTEN; AND HOW, AND IN WHAT FORM, WE ACTUALLY PERCEIVE THEM.

BY

CAPTAIN N. F. CAVE-BROWNE-CAVE
B.Sc., M.I.E.E.

A PAPER

Read before the Northern Centre of the Institution on the 5th November, 1930.

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Summary of Contents.

SOUND AND HEARING.

INTRODUCTION.

This paper was written primarily for those who are engaged in ordinary every-day telephone engineering—not for research workers, nor for transmission specialists. It is a broad survey of those aspects of sound and hearing which particularly affect the conversion of sound waves into some other form of wave, and their subsequent reconversion and reproduction as sound waves. Reproduced sounds, let us remember, are becoming of greater and greater importance every year in the daily lives of almost every one; immense industries are based on them; and the principles which govern their nature and perception are clearly of considerable moment. To take just one example, a knowledge of them is almost essential for intelligent broadcast reception.

For an understanding of this paper it is very desirable to have precise information as to the physical facts which govern the propagation and transmission of sound waves. For the convenience of those who have forgotten many of these facts, a short and elementary summary of the more important properties of sound is given in the Appendix. Such readers are earnestly recommended to study the Appendix before reading the paper. The paper describes, in turn, the nature of sounds, as produced; how we hear sounds; and the various causes, both within the ear and without, which lead to the differences between the sound originally emitted and what is perceived. Considerable space is given to the functioning of the ear, for the ear appears to be little understood by many engineers, though some of its peculiarities have important reactions on the reproduction of sounds. Further, few can fail to be personally interested in the ear, for it contains an amazing mechanism which is a beautiful example of Nature's supreme powers in the realms of design and contrivance. The information given is based mainly on the recent publications listed below, to which general acknowledgment is hereby made:—

(1) "Frequency Characteristics of Telephone Systems," by Capt. B. S. Cohen and Messrs. A. J. Aldridge and W. West (J.I.E.E., June, 1926).

(2) " Apparatus Standards of Telephonic Transmission, and the Technique of Testing Microphones and Receivers," by Capt. B. S. Cohen (J.I.E.E., February, 1928).

(3) " The Measurement of Sound and its Application to Telephony," a 1929 I.P.O.E.E. paper by Mr. A. J. Aldridge.

(4) " The Sounds of Speech," by Mr. I. B. Crandall, Bell Telephone Laboratories.

(5) " How we hear," by Dr. R. T. Beatty, in the December 11th and December 18th, 1929, issues of " Wireless World."

(6) " Modern Gramophone and Electrical Reproducers," by Wilson and Webb (Cassell & Co.).

(7) " Speech and Hearing," by Mr. Harvey Fletcher (MacMillan & D. Van Nostrand Corpn.).

This last book cannot be too strongly recommended to those interested in recent technical research. It has provided the figures for several of the diagrams, some of which, indeed, have been taken directly from it, and my thanks are due to Messrs. D. Van Nostrand Corpn. and Messrs. MacMillan for permission to exhibit and reproduce them. I owe thanks also to " Wireless World " (see (5) above), for permission to reproduce diagrams; to Mr. A. J. Aldridge for the loan of slides and exhibits; to the Birmingham Drawing Office staff for producing slides and diagrams; and to Mr. A. C. Smith for advice and assistance.

THE NATURE OF SOUND.

1. *Propagation and transmission of sound.*

Sound and hearing combine to produce a wonderful dual phenomenon, a complex mechanical action stimulating acute mental perception. Given a sound—which word really presupposes a listener—the whole process depends on a small masterpiece of nature, the ear. In the ear we have a beautifully designed mechanism for converting sound waves in the air into a pattern of nerve impulses to the brain. Though this converter is extremely sensitive over a wide range of sound, yet it is a marvellously compact structure.

Transmission of sound from source to ear is secured by longitudinal vibrations of a material medium, usually the air, and we call this action " sound waves." It is the waves we hear, not the source itself, because things can only act where they are. It follows that we get no sounds through a vacuum, and can hear nothing from outside our earth and atmosphere. Otherwise we might know more than we do of the colossal explosions continually occurring on the sun. Sound waves travel about one fifth of a mile a second in air. Light waves travel about a million times as fast, but they are non-material transverse waves in the ether of space. We are fortunate to find, in a world of noise, that the great forces of nature—gravitation, radiation and so on—are silent forces.

Waves, then, are necessary for hearing. A lady's fan works too slowly even to start a train of sustained waves—but not so a bee's wings. Some true waves vibrate too slowly for us to hear them, though we may perhaps feel them; and others are too rapid, though they make a flame flicker. The audible range covers a ratio of about 1,000 to 1 for frequency and many millions to one for power. Broadly speaking we can hear any waves which make a light diaphragm vibrate.

2. *Wave motion effects.*

Ripples passing across a pond give us a good mental impression of sound waves. In place of crests and troughs we have compressions and rarefactions of the air, and of course the air particles move backwards and forwards again and again for almost microscopic distances in line with the wave. They behave like a luggage train shunting backwards and forwards. The energy-carrying bumps and pulls, *i.e.*, the compressions and rarefactions, alone travel along. Unlike the " music " from an underwound gramophone, the wave, that is the loudness, dies away without drop in frequency.

Sound transmission, then, depends on a transfer of energy by sound waves. These waves normally spread out in every direction as they travel along, steadily expending energy in heating the air and on obstacles. As the waves spread, the power intensity per unit area of wave front surface diminishes, and as the waves travel along, their energy is slowly dissipated. Far enough away from the source the particle amplitude will be so small that the wave can be considered to have died away.

The energy of the wave is derived from the source of sound. If the supply of energy to the source ceases, its vibrations will soon die away, and waves will no longer be emitted. The speed or heaviness of this damping action will depend on the efficiency of the transfer of energy from source to wave, that is on the loading. Efficient wireless loud speakers provide a good example of successful loading. The source of sound here is a small moving coil, or iron armature, or diaphragm. Neither displaces much air, and so could not produce loud results if simply left open to the room. But we can fix a piston to the coil or armature and so make much more air vibrate at a high initial amplitude. With proper design we can thus provide a load, which will be suitably matched to the power available, and so will give loud and good reproduction. The old-fashioned diaphragm with small horn cannot possibly be loaded so as to reproduce low notes efficiently or adequately. If the horn be insufficiently rigid, we lose still further low notes; if it be rough, we lose high notes. An exponential horn is the only satisfactory solution. It ought to be very rigidly built and the longer it is the better, up to about 40 ft. long. Some modern gramophones have been enormously improved by an internal folding type of exponential horn, coupled with matched impedances right from the needle outwards.

Sound waves give us other well-known wave phenomena, such as reflection, diffraction, interference (or beats), and, above all, resonance. We get resonance when we have the frequency of a disturbing wave identical with the natural frequency of some object disturbed. Resonance is used, something on the lines of a telescope trained on to a particular object, to select some particular frequency and make it sound enormously louder. It operates by efficiency in loading and radiation. A sea shell of almost any size or shape will give us "the sound of the sea" when held to the ear. This is because the air always, and in all places, contains sound waves of nearly every possible frequency, though many are normally inaudible. The shell selects one or more of these frequencies by resonance and greatly magnifies its effect on the ear.

Except when single pure tones are deliberately produced, sound waves are found to be a compound of two, or of several, simultaneous waves of different frequencies. These may possibly be produced by a single source, in which case we usually find a fundamental and harmonics, or by many separate simultaneous sources. When dealing with electrically transmitted sounds, we must realise that widely different component frequencies may not always travel at the same speed and may thus show relative phase changes; also that some of the components may be of a transient character, so that their actual duration may be important in reproduction.

3. *Wave distortions.*

For a series of waves to be properly transmitted and reproduced, we must retain throughout in correct proportions:—

(1) The amplitudes which govern loudness;

(2) The frequencies which govern pitch; and

(3) The complex wave forms which give the characteristic timbre peculiar to the source. If some frequencies are reproduced unduly loudly, as by unwanted resonance, we get what is called frequency distortion; if one sound is not reproduced twice or three times as loud as a similar sound, though it was originally twice or three times as loud, we get amplitude or non-linear distortion; and if the true rapidly changing wave form is not reproduced, possibly due to phase shifts or inertia effects on transients, we shall get unnatural reproduction. Every care is necessary in reproduction to avoid introducing spurious component frequencies, either by non-symmetrical structures or by over-loading; and the high and low cut off frequencies must be as near to the audible limits as possible. If the lower notes in music are not well reproduced, we get a curious false sense of loudness when using a given radiated power. For with good reproduction of all frequencies the bulk of the power is in the bass notes; and then, with a limit of power in the reproducer, the high notes must of necessity be very feeble compared with how they sound when there are no low notes to absorb the energy.

Before dealing in detail with some of the scientific principles involved, it may not be out of place to get sound into true perspective by considering some of its properties, limitations and uses.

4. *General Properties.*

Our primary sense of hearing is one of Nature's most precious gifts. It is shared by animals and birds in general, but is either deficient or on quite a different plane in fish, insects and many of the reptiles. We hear from infancy untaught, though the brain has to learn to recognise sounds and later to interpret them from experience. In fact we cannot help hearing and often do we wish that we could close our ears as easily as we can close our eyes.

There are other interesting comparisons between our senses of hearing and seeing, as for example:—

(1) We see things in arithmetical progression, but hear them in geometrical progression. By this is meant that the eye will naturally measure off lengths or areas in equal steps, 1, 2, 3, 4, etc., as can be confirmed by a tape measure; but the ear, whether it is considering pitch or loudness, measures off as equal steps those steps which measuring instruments of frequency and power show to be actually in the geometrical series 1, 2, 4, 8, etc.

(2) Just as we have chords of colour in, for example, the colour pink in a printed picture, so also we have chords of sound. Now the ear can select and to a large extent concentrate on any frequency component it chooses from the sound chord, whereas the eye has no such power in a colour chord. On the other hand, where we have a panorama of sights and a number of identical sounds from several different directions, the eye can focus and concentrate on quite a small area of view, whereas the ear cannot at will select and concentrate on *identical* sounds from one area alone. So, broadly speaking, the ear has frequency but not area powers of selectivity and the eye vice versa.

(3) The eye is a much more ready judge of small differences and has a more retentive memory than has the ear. The old game of judging how far up a wall is the height of a top hat shows that the eye is not infallible, but the eye has the great advantage under most circumstances of being able either to compare two lengths by seeing them together side by side or to compare both separately side by side with a definitely graduated scale. Moreover, most people could construct a foot rule of fair accuracy without any standard rule to base it on. But the ear cannot hear two distinct *similar* sounds side by side yet separately; nor could any untrained person determine by ear alone even approximately either the frequency or the standard of loudness of some isolated sound. In fact, some authors state that few could say with certainty which is the louder of two sounds heard at long intervals of time unless the one sound contained some 10 times the power of the other; and few can determine the

relative power intensity of, say, a high-pitched whistle and a typewriter. Even when speech alone is listened to at varying loudness the power must be altered about 30% before the change is distinguishable. But this does not detract from the wonder of the ear, because a strong syllable if spoken loudly may have a million times the power of a soft syllable if whispered. Yet the ear can detect both—and in fact a range thousands of times greater than this—without difficulty or discomfort.

(4) We are used to regarding the eye as the standard guide for examining materials and products generally—sometimes assisted by smell or taste or feeling—but sound is also useful. For example, we make use of the " ring " of metals, porcelain, glass, etc.; the doctor uses his stethoscope, as also does the machinery expert; and with a microphone and amplifier it is now possible to " listen in " for the grape-fruit pest as it eats inside the fruit, whereas no eye can detect it from outside. In this way the transport of thousands of useless fruits is being avoided.

(5) The eye is the standard for judging distances, but sound can enable us to judge considerable distances when vision is impossible. Very high frequency sound waves can be focussed in a beam and directed towards a suspected cliff or iceberg. If such an object be near, the beam is reflected back to the ship and the time for the double journey shows the distance away. Similarly the depth of water can be measured. true " soundings " in fact. Or again a lighthouse or lightship can send out sound signals simultaneously through the air and the sea (or through either alone and by wireless), and the interval between the reception of the two will give the ship its distance away. In the war we had " sound ranging " for guns and " sound " detection of aircraft, submarines, and tunnelling parties.

(6) In our spare time occupations, too, the struggle of sound and light is as interesting as the battle of gas and electricity in another sphere. For years past we have been able to see objects scores of miles away on earth and untold thousands of miles distant in space, and we had drawings and pictures, and later, photographs. Later still we had stereoscopic photos and photographs in natural colours. Sounds could only travel a few miles and could in no way be recorded. But, under modern conditions, between the source of sound and the ear there may intervene the conversion of the air

waves into electro-magnetic waves in the ether and their reconversion to very similar sound waves in air after travelling thousands of miles in an instant. This may even happen more quickly than the original sound can reach people at the back of the hall in which it is produced. And whereas a great speaker or musician could once reach hundreds, if they could afford to listen, he can now reach millions at once at almost no cost to the listener. Thus, pending the perfection of television, the art of hearing current events at a distance is far more advanced than is that of seeing them. Or again, sound waves may now be converted into a mechanical gramophone record, a magnetic wire or strip sound record, or a picture sound film record, and subsequently reproduced as air waves, perhaps years or even centuries later. But, so far, no practical method has been developed for giving a stereoscopic effect to reproduced sounds.

(7) Pictures have undoubtedly the power of transmitting personality and emotions generally. Few can doubt, I think, that sound waves, too, can transmit personality, and those who have heard, say, Sir Oliver Lodge or Mr. Basil Maine by Wireless will know that personality can be transmitted even by reproduced sounds. So also can enthusiasm, excitement and emotions of various kinds.

These examples will suffice to indicate that the engineer who specialises in Sound is faced with many difficult problems, particularly as regards measurement and range. Under present-day conditions a telephone engineer must, in the most economical manner possible, using any necessary conversions and reconversions,

(1) Transmit speech and reproduce it so that it is not only intelligible, but is also sufficiently natural to be acceptable, and

(2) Transmit speech and music for broadcasting purposes with a minimum of frequency cut-off and distortion, which at worst must not exceed what is experienced with the best standard reproducers.

We will now study in some detail what these requirements involve.

5. *Speech, music and noise.*

The sources of sound can conveniently be divided into speech, music and noise. Music, which in some cases seems very like noise to some people, is broadly distinguished by the fact that it is an arrangement of particular frequencies which are sustained for appreciable periods; and that the frquencies used are in definite steps and relationships. Unintelligible speech is really noise, and, just as flowers in the wrong place are regarded as weeds, so any sounds are noise if they are extraneous to what it is desired to hear at the moment.

From another standpoint it is convenient to take speech and vocal music as one, because both are subject to Nature's limits. Both can be immensely improved by scientific training in production and by constant practice. Instrumental musical effects can largely be controlled by design. Instruments are divided into string, wind and percussion instruments. The organs of speech are really a wind instrument. Noise is purely accidental and unwanted.

6. *Sound measurements.*

It has been found very difficult to measure sound effects accurately, because of the great differences in ears, and because of the variable reports which any pair of ears is liable to give even from hour to hour. Reference should be made in this connection to Mr. Aldridge's I.P.O.E.E. paper which is listed above. The principle of the methods generally followed in research on sound is, first, to develop perfect reproduction; then to find the least measureable distortion; and finally to deal in multiples of this latter as a unit. There are, of course, variations in the methods of expressing the results. It is interesting to note that work by telephone engineers to obtain perfect reproduction for research work has led indirectly to the present broadcasting microphones; to electrical methods of producing gramophone records; to great help in measuring and alleviating deafness; and to the restoration of the power of speech to people who have lost the use of their vocal cords.

7. *Measuring units employed.*

To compare any property of one sound with the corresponding property of another sound, units of measurement are essential. The scales shown in Fig. 13 will assist in this connection. Units are required for the frequency, the amplitude, the root mean square (R.M.S.) pressure, the power, and the Power Intensity of the sound wave; and for the pitch and the loudness, or some similar unit, of the sensation produced. For frequency we use cycles per second, and for amplitude cms. The pressure is usually expressed in dynes per sq. cm. Atmospheric normal pressure is about 15 lbs. per sq. inch, or roughly one million dynes per sq. cm. The power may be measured in micro-watts (or millionths of a watt); and the Power Intensity at any plane in micro-watts passing any area of one sq. cm. For pitch, which is the level of frequency, it is convenient to use 1,000 cycles per sec. (C.P.S.) as zero pitch or reference level, and to measure pitch up and down in octaves or centi-octaves (c-Os). As each 100 c-Os up means doubling the frequency, and each octave down means halving it, a level of + 200 c-Os will represent a frequency of 4,000, *i.e.*, (1,000 × 2 × 2); and −300 c-Os will represent a frequency of 125, *i.e.* (1,000 ÷ 2 ÷ 2 ÷ 2). Thus the frequencies corresponding to unit steps on the pitch scale are in geometrical progression. This is called a logarithmic scale, and is very convenient. The piano keyboard is an example of this principle. It may be added that it is also very helpful to use a logarithmic scale for the level of Power Intensity. Here the standard step now most popular is the decibel. The decibel is a step representing a power intensity ratio of 1.259 to 1; or a 25.9% increase in Power Intensity. If we have sounds of two Power Intensities, P_1 and P_0, their difference in Power Intensity level, expressed in decibels, is defined as $10 \text{ Log}_{10} \frac{P_1}{P_0}$. If decibels are not understood, Para. 15 of the Appendix can be read now with advantage. The zero, or reference, level of Power Intensity, P_0, can well be taken as 1 micro-watt per sq. cm. This is about the level of Power Intensity produced by an average conversational voice at ½″ distance, and corresponds roughly to an R.M.S. pressure there of 20 dynes per sq. cm. Some examples of the wide range of values in question, given in Fig. 13 and referred to again later, show the absolute necessity for some such scale. With an arithmetical scale we should have to be writing power intensities varying from 0.000,000,000,3 up to 40,000 micro-watts per sq. cm., which correspond to R.M.S. pressures of the order of 0.0003 to 3,000 dynes per sq. cm. No practicable diagram could cover such a range. But calculating in decibels (db) we have a corresponding range of power intensity level of roughly −95 to +45 db, all parts being of equal significance. This necessity is unfortunate, because to the non-mathematical mind, this decibel system gives an appearance of fundamental complication, which has no existence. For similar reasons we have, for perception level, a logarithmic scale of Sensation Units. Here there is an actual and difficult complication, because at different frequencies, but at the same Power Intensity level, the magnitude of Sensation is found to vary very greatly. This is dealt with later. Here it can only be said that, taking any particular frequency, zero Sensation level is given to the lowest perceptible Intensity level. If we have a sensation S_1, one hundred times as big as this first sensation S_0, we should say that it has a Sensation level of +20 db because $10 \operatorname{Log}_{10} \frac{S_1}{S_0} = 20$. For speech, a sound of many frequencies, and for tones of Pitch about +1 octave, it is usually taken that Power Intensity level (P.I.L.) 0 corresponds to Sensation level (S.L.) 100, and similarly −100 (P.I.L.) corresponds to 0 (S.L.), and +40 (P.I.L.) to 140 (S.L.). See the scales of Fig. 14. The Intensity level gives a measure of mechanical action; the Sensation level a measure of the resulting mental impression. This impression is of necessity individual, but it can be averaged.

It may be added, for comparison, that the removal of 1.129 miles of "Standard Cable" from a telephone receiving circuit will increase the power available in the receiver by 25.9%. We can thus say that 1 decibel is, in a sense, equivalent to 1.129 miles of "Standard Cable." The change of cable is the cause; the decibel change in power is the effect. Those who must visualise decibels can do so in this way—with reservations. Similarly we can say that 1.129 M.S.C. added attenuates the power available by 1 db, equivalent to a 20.6% power loss.

CHARACTERISTICS OF SPEECH AND MUSIC AS PRODUCED.

8. *Some general properties of speech.*

In speech we have something much more than the monotonous speaking of a series of words. Apart altogether from gesture and facial expression, we have the characteristic timbre of the voice speaking, and also varying rhythm, intonation, inflection, expression and exact pronunciation. The origin of speech is an interesting speculation. A word like hither is supposed to have been derived from a beckoning action of the tongue. Some words are certainly suggestive of their meaning; most others are at any rate not unsuitable. We could not well imagine a reversal of the meaning of the following pairs of words:—thin and stout; whistle and drum; sonata and jazz. In learning to *speak* a language properly, the actual words (letters) are only a part of the problem. Pronunciation, rhythm and inflection are all enormously important, and are a great obstacle to the popularising of a universal *spoken* language. Many of the muscular movements and adjustments are complex and obscure, and take years to learn properly. We English, for example, have learned from infancy how to produce an "H" sound. Here is a problem for a Frenchman who is trying to learn English from a book, yet has never pronounced an H in his life, and does not know how to go about it. With a few such exceptions, the fundamental speech sounds and syllable sounds are much the same in all languages, though very differently and variably spelt. It is surprising to find that five fundamental speech sounds, I (as in tip), N, T, R and O (as in ton) are together more than $\frac{1}{3}$ of the total sounds (not different sounds) actually used in English; that ten syllables (the, of, in, and, I, O, Too, In, Or, ri) are more than $\frac{1}{3}$ of the syllable sounds; and, most astounding of all, that seventeen words (The, of, and, to, a, in, that, it, is, I, for, be, was, as, you, with, he,) are a third of the words occurring in ordinary English. This means, of course, that of any, say, 3,000 successive words, (not different words) ordinarily used, 1,000 will be one or other of these seventeen words. Tests show that the following fundamental speech sounds are the most difficult to hear correctly, the numbers following them being the approximate percentage of times they are misinterpreted: —th (as in thin) 17%, f (as in fall) 13%; and next follow in order, though not very definitely, v, e, p and the vowel sounds in "rook" and "spool" (from 4% downwards).

9. *The production of speech sounds.*

The organs of speech consist of the vocal cords, the tongue, the mouth, the throat and nasal cavities, the lips, and the teeth. The vocal cords are actually two muscular ridges with a slit between them and are not in the least like violin strings. Air passing between them is set in vibration by them, and they give the pitch of the sound and, to a large extent, the characteristic timbre by which the voice can be recognised. Broadly speaking, consonants are different ways of starting and ending vowels; vowels are produced by varying the strength and damping of the various harmonics of the fundamental vocal cord frequency. This is done by varying resonances in the mouth and in the throat and nasal cavities. Speech sounds can, indeed, be picked up directly from the outside of the throat. During part of the war, special observers' hand sets and aviators' head equipments were designed containing throat microphones, and much extraneous noise was thereby excluded.

While a speech sound is being spoken, the form of the wave emitted will vary very much. Oscillograms will trace in great detail these changes of wave form from instant to instant.

Fig. 1 shows four periods, each of 1/100th of a second, for the sounds "SA" and "MOO," both spoken by male voices. The high frequency "S" part and the quite different "AH" part are clearly shown. The "M" and

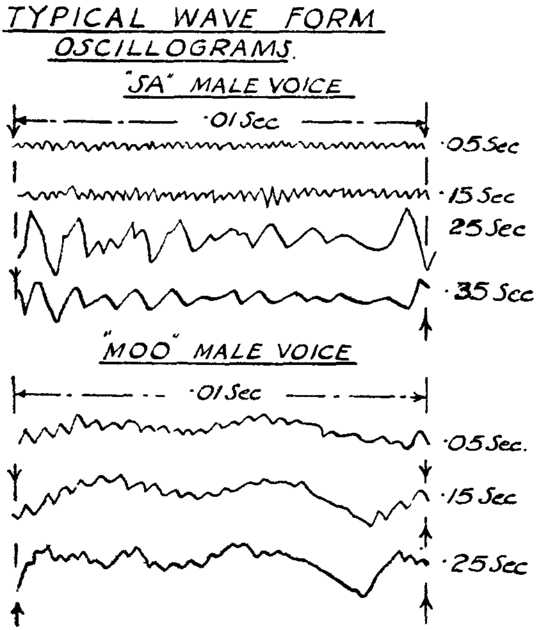


FIG. 1.

" OO " are also characteristic. Fig. 2 shows similarly " LEE " and " LA," and is particularly interesting because, though the " L " and " AH " parts are quite different, the " L " and " EE " parts appear almost identical.

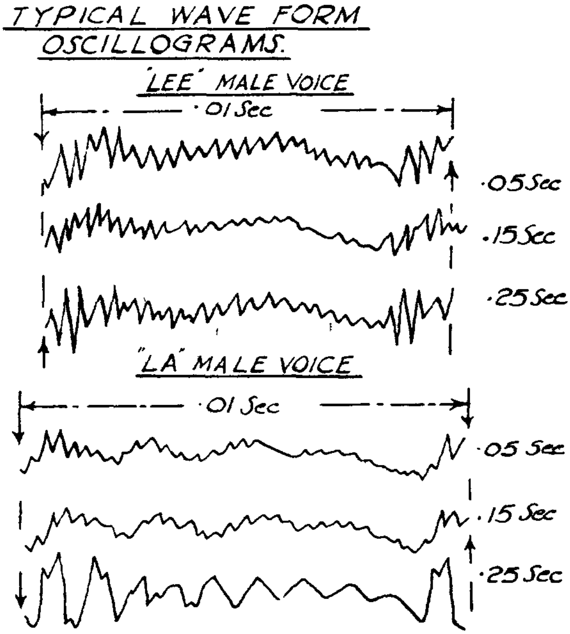
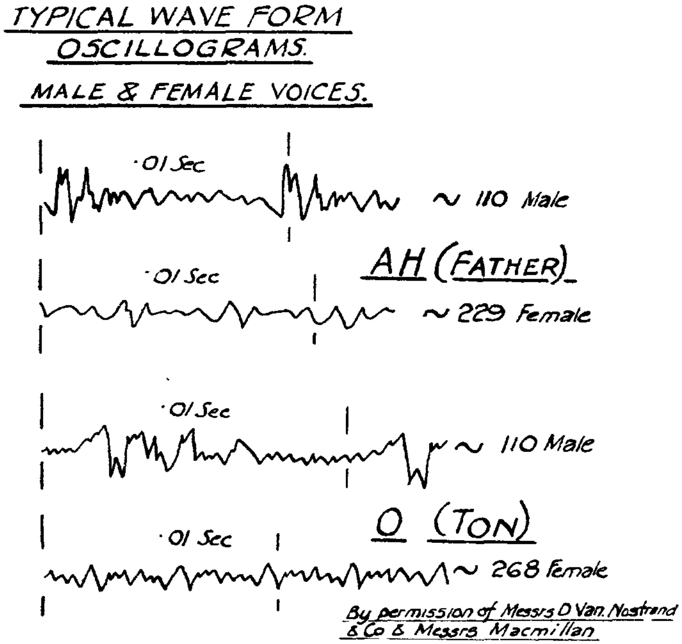


FIG. 2.

Fig. 3 gives the wave forms of AH (as a in Father), and " O " (as in Ton) spoken by male and female voices. It shows that, to the inexpert eye, the two male and two female wave forms are much more like each other than are the male and female wave forms of either word. In Fig. 4 are shown the spectra of the sound " Long E " (as in eat) when spoken at fundamental frequencies of 128, 192, and 256 C.P.S. A spectrum shows the relative value of the amplitude of each harmonic produced, but takes no account of the relative lack of response in the ear to the lower frequencies nor of subjective harmonics. It will be seen that the two main resonance areas which are characteristic of " long E " remain roughly the same at the three frequencies. The spectrum of every vowel sound shows one resonant frequency area, or a pattern



(From "Speech and Hearing.")

FIG. 3.

of resonant areas, peculiar to itself. Sir Richard Paget has demonstrated that typical vowel sounds can be artificially created and controlled by producing pure wind tones in pipes and combining them in patterns of harmonics similar to these.

Now some of our English speech sounds are easily confused with each other, and particularly some of our letters when spoken as such. For example, telephonists are taught to say " fife " for five, to avoid confusion with " nine," and when words of a telephoned message are being spelt, it is a great help if the sounds ack (a), beer (b), don (d), emma (m), pip (p), esses (s), toc (t), and vic (v) are systematically used in place of the letter sounds in the brackets. No confusion should then be possible. Also, in speaking numbers, it is of assistance to the listener if the numbers are broken up in a standard way; for example, 5991 should be given as fife nine—nine one, and 5999 as fife nine—double nine. Thus the production of speech sounds can often be systematised with great advantage in transmission,—a fact well known in all communication services.

TYPICAL ACOUSTIC SPECTRA

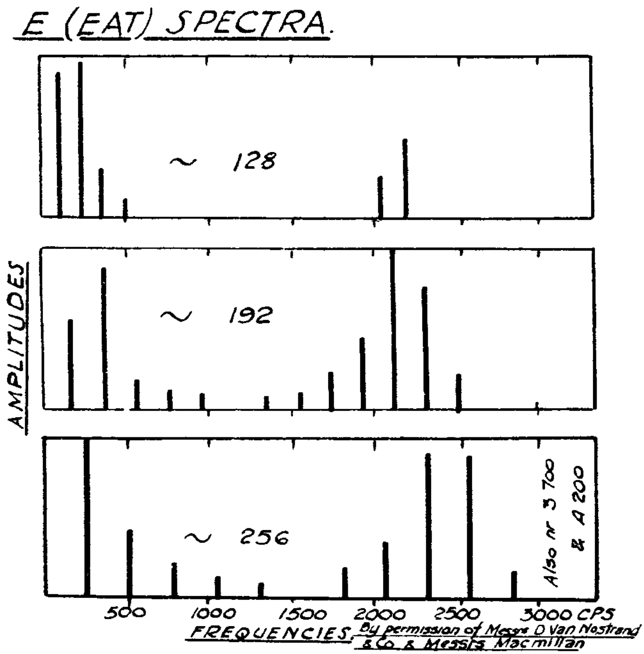


FIG. 4.

10. *Some measurements of speech properties.*

While speaking with steady effort there is found, with an average voice, to be a power variation of about 700 to 1 between the most powerful vowels, as in "talk" and "father," and the softest consonant (th in thin). In ordinary conversation, and without raising or lowering the voice, an average speaker will radiate about 10 micro-watts of speech power, which gives a power intensity of about 1 micro-watt per sq. cm. at $\frac{1}{2}''$ from the mouth; but if he speaks very loudly the power may rise to 1,000 micro-watts, and if he whispers it may fall to .001 micro-watt. On the average, the power derived from the lungs when speaking is some 500 times that radiated as acoustic power, yet is less than 1% of the power of the heart's work in circulating the blood (say, 4 watts); one small electric lamp radiates in heat and light as much power as do one million speakers in sound. Some 15% of people, when speaking at their normal power level, speak with less than $\frac{1}{8}$ of the average power as found for large numbers of people; and some 5% speak at from 4 to 8 times the average power. Telephones must accommodate all these big variations. The most important speech frequencies cluster around 600 and 1,800 C.P.S. About 300 to 2,400 C.P.S. are the limiting frequencies usually transmitted by telephone. An air particle amplitude near the mouth of about sixty micro inches (or millionths of an inch) represents good speech.

11. *Some general properties of musical sounds.*

Music is capable of expressing in the highest degree both intellect and emotion. Looked at merely as sound, we find that the harmonics of the fundamental are of very great importance, and their relative amplitudes and damping are the determining features of the characteristic timbre of the instrument.

Fig. 5 shows the wave forms, and Fig. 6 the amplitude spectra of a piano and an organ pipe, each played at a

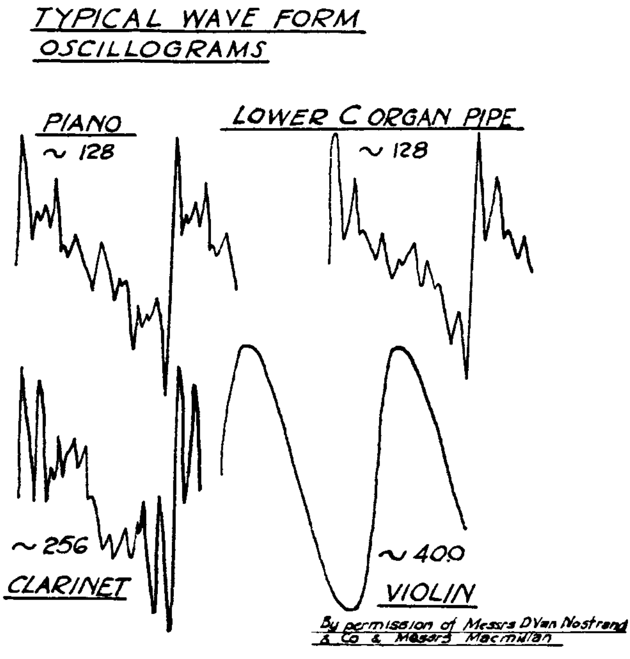
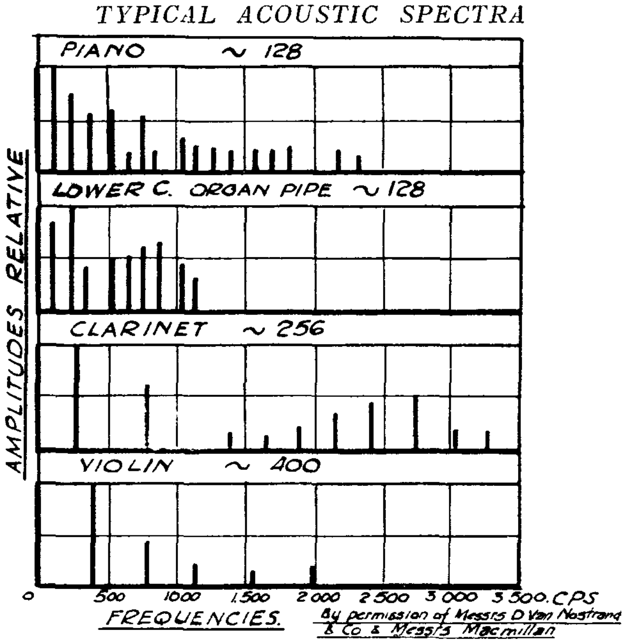


FIG. 5.



(From "Speech and Hearing.")

FIG. 6.

fundamental frequency of 128 C.P.S.; also of a clarinet at fundamental frequency 256 C.P.S., and of a violin at fundamental frequency 400 C.P.S. The wave forms of piano and organ are somewhat similar, but the spectra illustrate the different timbres. The clarinet, and violin wave forms are as different as their spectra. The great relative amplitudes of even the 9th and 10th harmonics of the clarinet may be noticed. With a 'cello organ pipe the third harmonic has double the amplitude of the fundamental. With drums, cymbals and xylophones, which are percussion instruments, any harmonics there may be are of relatively insignificant amplitude. Their overtones are mostly in-harmonic upper partials of a transient nature, for which the time of duration and relative phases are important. Good transmission and reproduction of them are found to be difficult.

12. *The production of musical sounds.*

We have to deal with percussion instruments, such as drums and xylophones; wind instruments, such as organs, tubas and cornets; and string instruments, such as violins and 'cellos, where the strings are bowed. The strings of a piano, however, are struck and then damped, and the sound can be sustained at will by checking the dampers. Forced vibrations and transients are produced by these blows, which make the piano, like other percussion instruments, a difficult instrument to transmit and reproduce faithfully. That organ tone which has a bleating timbre is produced by emitting simultaneously two tones of nearly equal frequency. The two tones together produce beats. In all musical instruments the pattern of overtones gives the " colour " of the sound produced, so that a " note " means far more than the fundamental frequency alone. The first harmonic only, together with the fundamental, is usually enough to make an instrument recognisable when other harmonics are filtered out.

Beautifully shaded chords and sequences of sound are designed by great composers. They utilise different instruments and combinations of instruments to give these shades of feeling, just as we use different words to give different shades of meaning. Music, however, can show a much greater range and delicacy of shading than can words. Thus any serious wave-form distortion in reproduction will more or less ruin this shading. So for broadcasting purposes telephone lines should have exceptionally good transmission characteristics.

The correct production of the voice in singing is a great art in itself. Here, again, success is based on the correct control of harmonics caused by resonances. The vocal cords, the mouth, and the throat and nasal cavities all have their share. Thus a singing voice also has a characteristic timbre, which is based largely on its pattern of harmonics; and it retains this timbre over a wide band of fundamental frequencies. The speaking voice behaves similarly. Hence for a voice, when reproduced by telephone, to be natural and pleasant, as well as intelligible, serious wave form distortion must be avoided.

13. *Ranges of measurements in music, including singing.*

Many musical instruments are so constructed that they *sound* nearly equally loud all up the scale, when they are played with equal effort. To do this the power intensity is made much higher by deliberate design for the lower frequencies than for the higher. This compensates for the ear's very heavy discrimination against the lower notes. As an idea of loudness, the sensation level of an organ in a theatre may be some 40 to 50 db average. In a single piece of music an orchestra may play with a power variation of 100,000 to 1, a variation very difficult to reproduce. A strongly bowed 'cello will give a power ratio of 100 at frequency 128 C.P.S. to only 1 at 650 C.P.S.; but a good violin will give a much more uniform power output between about 200 and 1,200 C.P.S. A singing voice, on the other hand, is fairly uniform in power output in its middle and upper registers, with a big drop in power towards the lowest pitched note which it can sing clearly. Here the power may fall to about one thousandth of the higher amount. This serious limitation of vocal power at low frequencies suggests some interesting possibilities in making singing, when reproduced, sound better than the original. For we can easily provide discrimination in favour of the lowest notes by suitable amplifying devices. Vastly greater power is radiated in singing than in ordinary speech. This power may reach as much as 30,000 micro-watts, as compared with the 10 micro-watts of average conversation.

Fig. 7 shows the ranges of frequency of the fundamentals of several instruments and singing voices; and gives an approximate guide to their relative R.M.S. pressures when they are played loudly. The R.M.S. pressures are measured in dynes per sq. cm. at 18 inches distance. The plan of the piano keyboard is used as a convenient frequency scale, all the frequency ranges shown being strictly proportional to its scale. There is also shown the range of audible frequencies and the ranges reproduced in various grades of transmission systems. This will be of use in considering the problem of transmitting broadcast music, as well as speech. Finally, the frequency range of a good modern gramophone is shown for comparison. The corresponding pressures shown are unexpectedly uniform, and it is surprising to see how relatively powerful is the full strength of the human singing voice. The piano and violin are noticeable for their big range of fundamental frequencies. The ranges shown do not, of course, include the harmonics. As few can hear anything above the "audible range" shown, many powerful harmonics are too high pitched to be audible. This effect causes high pitched fundamental notes to sound relatively thin or lacking in richness. In fact harmonics spell richness and are the basis of "a fine resonant voice" for example.

TYPICAL FREQUENCY RANGES, AND RELATIVE PRESSURES WHEN LOUD.

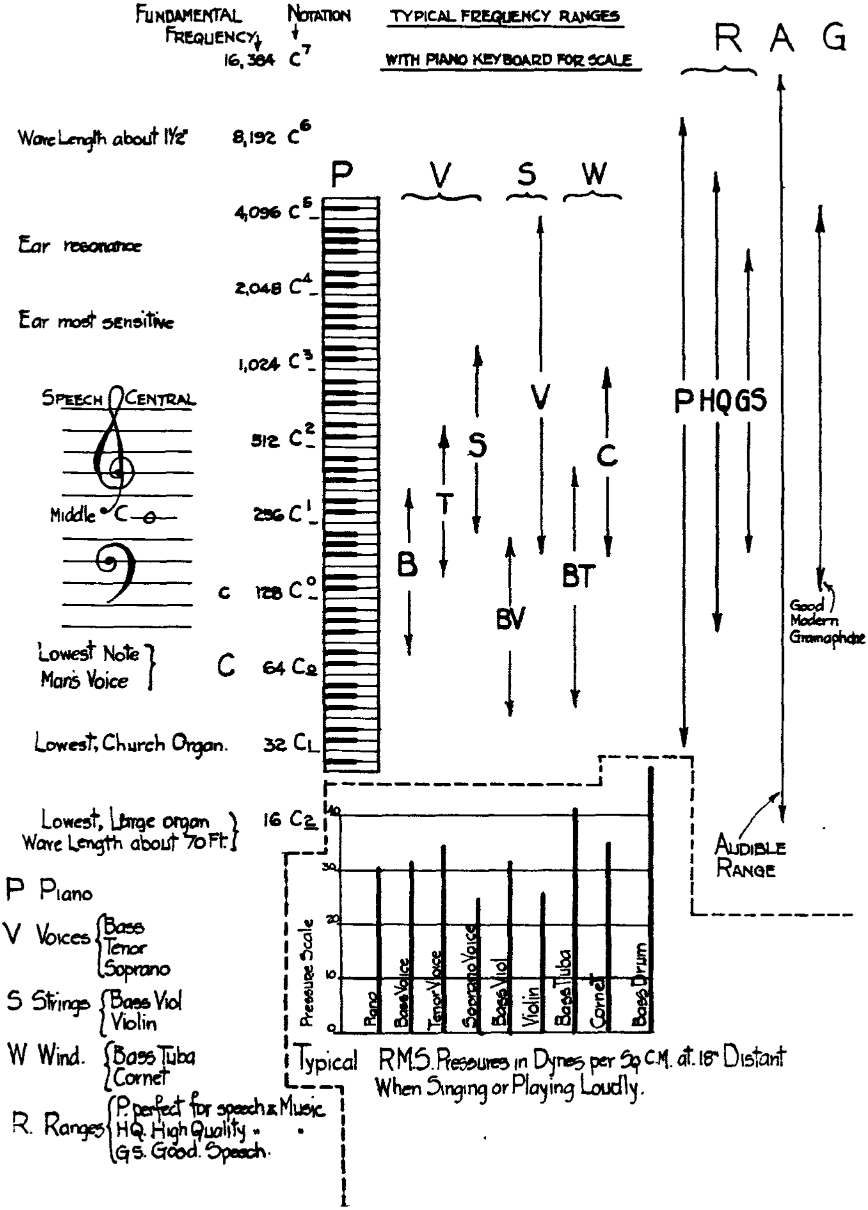


FIG. 7.

THE MECHANISM OF HEARING.

14. *The structure of the ear.*

The upper part of Fig. 8 gives an idea of the structure of the ear. The outer flaps of human ears are of no active assistance in hearing, whereas those of dogs or donkeys, for example, are. For the latter's can be turned to help to concentrate the sound, and also to locate it. Sound waves pass along the outer ear passage, which is some $1\frac{1}{4}''$ long, and beat against the ear drum. This drum is a diaphragm dividing the outer from the middle ear. The middle ear

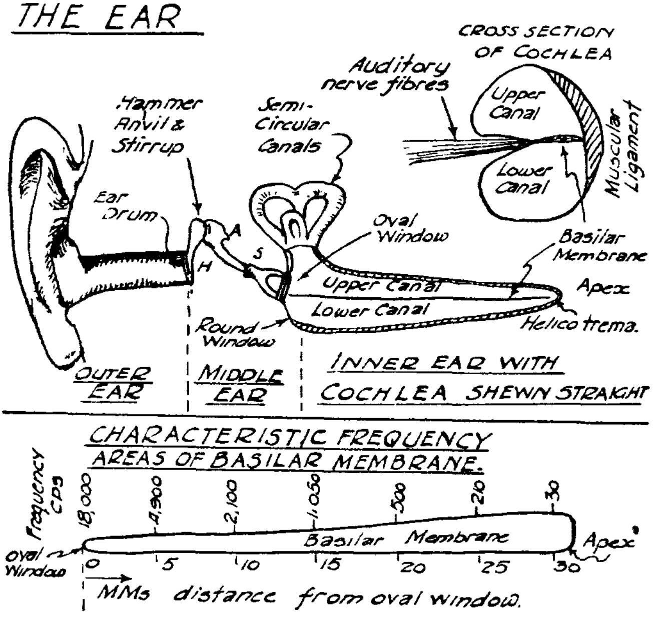


FIG. 8.

consists of a lever mechanism, which is formed by three small bones—the hammer, the anvil and the stirrup. The last named presses against a small oval window, behind which is a liquid, which carries the sound waves in the inner ear. The middle ear, by virtue of the bone lever system and because the oval window is much smaller than the ear drum, gives pressure variations on the liquid some 50 to 60 times as great as the air pressure variations on the ear drum. A fine tube passes from the middle ear to a point in the throat behind the nasal opening, and serves to equalise the *steady* atmospheric pressure on both sides. It sometimes carries germs to the ear and causes a gathering.

The system of the inner ear is difficult to describe. Fig. 9 shows the curious canal system concerned, full of a liquid lymph. On the left of the oval window three semi-

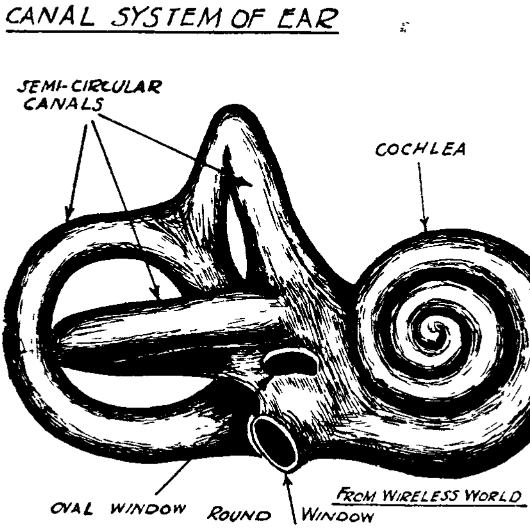


FIG. 9.

circular canals are shown, which take no part in hearing, but help us to maintain equilibrium and judge our movements. *These* are common to all birds, reptiles and fish, as well as to mammals. On the right we have a spiral canal which is divided into two main separate canals, except for a small connection or passage way at the apex. This structure is called the Cochlea, and the passage at the apex the helicotrema. A minute object could pass along the top canal to the apex, through the helicotrema, and back down the lower canal. The latter terminates at the round window. Slow pressure on the oval window, in fact, causes the liquid to move in just this way, and to give a bulge at the round window. Fig. 10 shows the bony shell-shaped double gallery into which this Cochlea, with its $2\frac{3}{4}$ turns, is built. The bony shelf, which partly divides the canals, carries the auditory

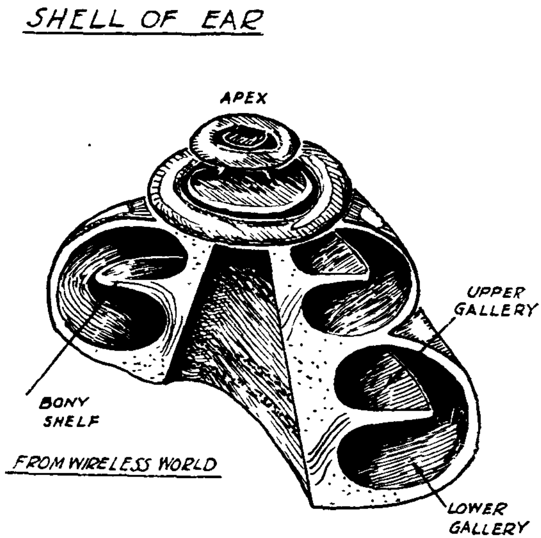


FIG. 10.

nerve fibres. The division is completed by what is termed the basilar membrane, about $1\frac{1}{4}''$ long and $1/15''$ wide, which is held to the outer wall by a muscular ligament. Connected therewith is what must surely be one of Nature's masterpieces. (Exact anatomical details will not be attempted. It is desired to explain the principles and the principal parts only). Here is the connection between the vibrating liquid and the nerve fibres, and herein is a mechanism able to distinguish extremely small changes in both frequency and intensity—a mechanism too, which is sensitive to an amazingly large range of power or intensity. The highest possible quality electrical power measuring instrument is, relatively, crude beyond words.

Referring back to Fig. 8, at the right this canal system is shown both in section and straightened out. Actually the upper canal is a double one, but this we may ignore. The clue lies in the flexible basilar membrane, which divides the upper and lower canals and is directly connected to the nerve fibres. In connection with this small membrane are no less than some 23,500 tuned strings, each having some 12 to 15 hair endings lying in the liquid. The string system, which resembles that of a piano or harp, is connected back to some 3,000 nerve fibres, which go to the brain. At the lower end of this membrane are the treble strings, tuned some two octaves higher than the highest strings of a piano; at the apex are the base strings, tuned about an octave lower than the lowest strings of a piano. At the bottom of Fig. 8 is shown to what part of the $1\frac{1}{4}$ inch length of this membrane, approximately, Science assigns a whole range of characteristic and exclusive frequencies. This result has been attained by scientific experiments of a high order.

If a wave of a single frequency enters the ear and agitates the liquid in the upper canal, it is found that not only is there a transfer of vibrations to the lower canal through the apical passage, but also, due to resonance, there is a very much more efficient transfer of vibrations directly through a particular part of the basilar membrane. This localised agitation would, as Fig. 8 shows, be towards the apex end for vibrations of, say, 200 C.P.S.; for a frequency of, say, 1,000 C.P.S., the agitation would be near the middle of the length of the membrane; and for one of 12,000 C.P.S., close to the bottom end, *i.e.*, between the oval and round windows. In other words, the membrane behaves as if it were tuned. The tuning is given naturally, because the nearer we get to the apex, (1) the longer are these strings (.4 to .13 mm), (2) the more loosely are they stretched by the muscular ligament and (3) the more heavily are they loaded, especially by the mass of liquid to be moved to reach them. The whole action depends on resonance. This selective vibration of the membrane is thus of fundamental importance. This marvellous economy of space is rendered possible because of the infinitesimal nature of the powers and of the amplitures of vibration involved. The movement is probably much less than a millionth of an inch, and it has been calculated that the tightest strings have probably a factor of safety of four or so.

15. *Nerve action.*

When the sensitive hair-ends and their corresponding tuned strings are caused to vibrate by the sound wave, *via* the lever and canal systems, the sensory nerve fibres send pulses to the brain, the combined results of which give us "Hearing." These pulses, however, are in jerks of fairly uniform magnitude for any fibre. When the stimulus is the softest audible, a single fibre sends pulses at slow regular intervals; as the stimulus increases, this fibre sends equal pulses at shorter and shorter intervals, with a limit; and then more and more adjoining fibres start pulsing more and more often. Hearing is thus based on a discontinuous process, very different from sound waves, and stops suddenly and absolutely at a definite low intensity level. It operates like bullets from a battery of machine guns. The locality of the most active fibres gives the clue to the pitch of the note, based on what we may call a space pattern; but it is likely also that the time pattern of the pulses helps the brain to determine pitch. This may well be so if each pulse occurs at some particular point in the stimulating cycle—not in every cycle—and at no other point. The magnitude of sensation is given by the total volume of pulses reaching the brain; the loudness of the separate notes of, say, a three note chord, by the volume of pulses in the three separate relative brain areas.

The tone which is just too low-pitched to be audible is reached when the liquid lymph is moved bodily through the helicotrema; and the tone which is just too high-pitched to be audible, when the mass of the bone lever system is too great to respond. For these two limiting frequencies there are no vibrations of the basilar membrane, and incidentally there are no strings which are tuned to respond to them. For any single pure tone, the string response curve, taken along the basilar membrane, will be sharply peaked at the point corresponding to the exact frequency of the tone. But there will also be a tapering-off response from adjacent strings above and below these. The louder the tone, the more will this overlap be; and any freqeuncy area, thus caused to vibrate, will be proportionately less sensitive to any other separate simultaneous tone of that frequency. In fact, localised " masking " will occur, the extent of which is dependent largely on the loudness.

The nerve fibres, after each pulse, have a refractory period of about .001 sec., during which they cannot send another pulse; and a semi-refractory period of .003 sec., during which any pulse sent will be of less than normal strength—an overload effect. The 3,000 fibres, each with a core surrounded with a kind of insulation, form something resembling a cable. This cable would pass through the valve tubing in a bicycle tyre. The whole Cochlea system would go into a pigeon's egg.

The following fairly accurate analogy will help us to fix the general system in our minds:—Imagine a 3,000 wire telegraph cable arriving at a telegraph office, where it is connected to suitable receiving apparatus. Imagine is to be connected also to a sending office with 3,000 Multiplex manual sets, manned by 23,500 telegraph operators, each (for this occasion) with some fifteen ears. The operators in each small group are taught to signal, so far as they can judge, only when they hear a definite musical tone, peculiar to that group; and to signal at a definite slow rate when they can just hear their tone, and faster and faster the louder the tone sounds. As pure tones are sounded, so signals will be sent out on definite conductors. If the tones are fairly loud, signals will come in fast on a few such conductors, and also more slowly on adjoining ones, owing to misjudgments of pitch. If the tones are really loud, some operators will be keying so quickly that bad contact will be made and full current will not be received. When in any area all are going at full speed, no increased out-put is possible in that area however loud its notes. By suitably grouping and recording the incoming signals, the receiving office could tell just what single notes or chords were sounded, and when, and about how loud. With a suitable moving record strip, with 3,000 inkers laid out in proper order, we should get a space pattern of the note areas across the strip, and also some kind of a corresponding time pattern along the various intermittent inker lines running parallel with the strip. If it were possible to analyse in detail the collection of pulses sensed by the brain, they would probably show a pattern of this type; but, for exactitude, the operators would have to synchronize each signal with some single standard point in the wave cycle which stimulated it.

16. *Location of sounds.*

The position of the head between the ears causes in most cases sufficient difference in the sounds received by the two ears to enable us to judge distance and direction. This has been found to be due mainly to the creation by diffraction of a difference in phase between the ears; the two ears experience also a slight difference in loudness. For high notes above about 1,000 C.P.S., this judgment usually fails. It is much easier to locate familiar sounds; and these, indeed, can often be located by one ear alone, but only these. Interesting experiments in sound location can be made with two coins snapped together, whilst the listener's eyes are covered up. We can sometimes feel certain that a sound is to our right or to our left; but we may feel uncertain whether it is in front of us or behind, because each may cause an almost identical variation in phase.

17. *Ears and learning to speak.*

The upper part of Fig. 8 is mainly due to Major F. Reid, who has drawn attention to the similarity of the lay-out of the tongue, of the Cochlea when drawn straight, and of the auditory nerve also. He has propounded the interesting and suggestive idea that there may be an unconscious signal system between the sensory nerves of the Cochlea and the motor nerves of the tongue, which would give a *natural* suggestion to an infant as to how to control the tongue, (and with it presumably the lips), in order to imitate speech sounds heard by it. According to the National Institute for the Blind, blind babies learn to speak as early as others, and blind adults learn to *speak* foreign languages as easily as do others. This shows that speech sounds are not learned partly by copying the facial movements observed in others. Now Sir Richard Paget traces the far-back *origin* of speech to the natural imitation of mainly manual gestures; but with blind babies, manual gestures are practically unknown. It is therefore interesting to speculate how far each phenomenon may affect the present day *acquisition* of speech, or how far we learn by nothing more than trial and error, repeated again and again. It is worthy of note that children who are stone-deaf cannot learn to speak,—except possibly by some special method, such as is now under trial. With this process a teacher makes an elementary speech sound in front of a gas flame, and thereby causes it to give a characteristic flicker. The pupil then makes sounds till he can reproduce this flicker. He can thus learn to recognise visually a succession of sounds which he can identify with their written forms.

18. *Non-human ears.*

It has been noticed that nature has developed the most sensitive ears in animals which are either hunters or hunted. The guinea pig's ear, besides having a Cochlea of 4 turns against our $2\frac{3}{4}$, has the exclusive and (one would imagine) uncomfortable property of giving a muscular twitch whenever a sound is sensed. This has assisted physiologists enormously in proving in detail some of the remarkable properties of the basilar membrane. The ears of a dog are far more sensitive than those of man and he can hear notes much higher pitched than we can. Special whistles are made on this principle which will call dogs without disturbing neighbours.

COMPARISON OF SENSATION WITH SOUND STIMULUS.

Our ears do *not* give us a true picture of the sound stimulus for three main important reasons:—

(1) Internal bias against the low notes (Para. 19).

(2) Subjective harmonics at moderate and high intensities (Para. 20), and

(3) Subjective difference and summation tones in the case of harmonic complex sounds (Para. 21).

These distortions are additional to the facts (1) that almost every sound received comes not only from a direct sound wave, but also from waves which have come indirectly after reflection from various walls and angles; (2) that sometimes there is a persistence of certain sounds in a locality due to unequal and unsuitable damping; and (3) that when all nerve fibres in any area of the ear are approaching their higher rates of pulse discharge, double the stimulus cannot produce double the pulses. This is of great importance at loud intensities. There is practically no persistence or hang-over generated in the ear itself, except after sounds which are uncomfortably loud.

19. *The ear's bias against low-pitched notes.*

The structure of the ear leads to its being rather insensitive to very high-pitched notes, but—more markedly—to its being relatively less and less sensitive the lower-pitched the sounds are, so long as they are below about 1,000 C.P.S. This is partly due to the greater mass of liquid to be moved to reach the corresponding resonant area of the basilar membrane, *i.e.*, towards the apex; and partly to the nearness of the helicotrema, which acts as a by-pass. The great magnitude of this bias is shown in Fig. 13, and is discussed later, particularly in Para. 24. If the whole intensity level of a piece of music as received be halved, many low pitched (and a few extremely high pitched) notes may drop completely below the lowest audible level, *i.e.*, below the horizon of audibility. The tonal balance is then upset. It will be seen later that this bias effect is very much less when the power intensity level is very high. The reasons given above for the bias would lead us to expect this.

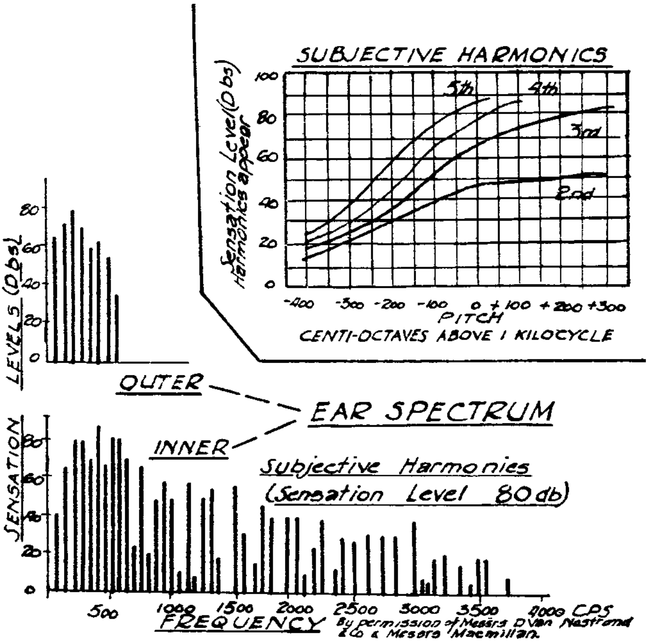
20. *Subjective harmonics at moderate and high intensities.*

The middle ear mechanism does not give perfectly symmetrical action, and so introduces what is called non-linear distortion. This leads to the production of harmonics of any tone received. This effect is very much greater at high intensities and low frequencies, and is inappreciable at low intensities. If, for example, we produce a pure tone C^0, *i.e.,* C below middle C, we perceive that tone alone if it is not loud. At a little louder intensity, we " hear " middle C (C^1), the second harmonic, as well. If louder still, we " hear " also perhaps C^2 and C^3, and louder still also C^4 and C^5. These are phantom sounds, in the sense that we could not detect them in the room by resonance with a suitable disc; yet these sounds are so real in the inner ear that we can obtain beats with them. We know that they are produced, and exist, in the ear alone, and they have most important effects on sensation. For we normally hear music at a sensation level of 50 to 100 db. For a low frequency such as 60 C.P.S., or a pitch of −400 centi-octaves, we can " hear " a second harmonic at only 12 db and the fifth at only 21. But at above 1,000 C.P.S., or zero pitch, we do not hear the 2nd till about a sensation level of 50 db, nor the 3rd till about 65 db and upwards.

Fig. 11 shows curves for this effect; it also shows the great difference between the spectrum of a loud complex sound in the outer ear, and the spectrum of what is actually conveyed to the inner ear. Such subjective effects must be of indirect importance in the design of transmission lines.

21. *Subjective difference and summation tones.*

If we produce three loud tones in harmonic series, such as 500, 600 and 700 C.P.S., we find that we get a very important phantom tone of 100 C.P.S., (600-500 and 700-600), which will actually cause the sound to be sensed like a musical note of frequency 100 C.P.S. This is the subjective difference tone, which, like subjective harmonics, is produced by lack of symmetry in the ear, particularly in the middle ear. If this subjective difference tone be loud, we shall have subjective harmonics of it as well. 1100 and 1200 tones would be present as subjective summation tones, but would

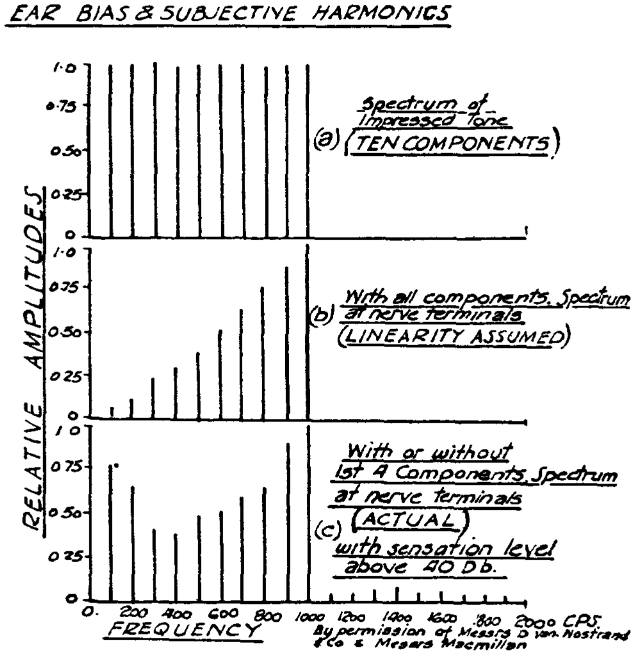


(From " Speech and Hearing.")

FIG. 11.

be little if at all noticeable. If, however, the tones were not harmonic, say were 500, 700, 900 C.P.S., we should get a sense of frequency 200 C.P.S., but the effect would be unmusical and noisy. Somewhat similarly it is sometimes possible to hear a phantom difference tone from two bird notes, each of which is too high-pitched to be audible.

Fig. 12 shows how great can be the combined effects of bias and subjective tones. Fig. 12 (*a*) shows the true pressure spectrum of ten pure tones of 100, 200 up to 1,000 C.P.S. These were produced simultaneously and of equal intensity, say 40 db or over. Fig. 12 (*b*) shows the *perception* spectrum taking the non-linear bias into account, but not the subjective tones; and (*c*) shows the actual perception spectrum, including both the bias and the subjective tone effects. The fundamental 100 is now brought up almost to its original importance. Further, when the fundamental and next three components were entirely suppressed at the source, the ear



(From " Speech and Hearing.")

FIG. 12.

was almost unable to detect the difference, provided that the sensation level was above about 40 db. This means that Fig. 12 (*c*) still held good for the perception of 6 tones only out of 10. This is an extremely important effect. When, however, the original 10 tones were produced very softly, the listener perceived a spectrum like (*b*). This was because the bias against low pitched tones was very strong, and the intensity of the tones was too soft to produce subjective tones. But even at these very low intensities the brain still senses the missing 100 C.P.S. in the 6 tone case, probably due to the pulsing action of each nerve fibre synchronising with some one particular point in the cycle which stimulates it.

22. *Musical quality variations.*

We can now see how enormously our perception of any musical sound, especially a complex one, will vary with its intensity; and we can understand why, for perfect reproduction, it is recommended that the final loudness at the ear should be as nearly as possible equal to that intended for direct listeners. Let us consider a further effect. A good horn loud-speaker is a poor instrument when played quietly, because it sounds like the original heard so far away that the deep-pitched tones have all fallen below the horizon of hearing (see Para. 24). But if it be played loudly, without overloading, we feel certain that we get good reproduction of deep notes, such as are produced by a bass viol or bass tuba. Such notes are lower than we are assured that the loud-speaker can possibly emit. This is because we have conditions similar to Fig. 12 (*c*). The loud-speaker is producing the middle and higher harmonics, and the fundamental and lower harmonics are completely missing. They would not cause resonance with a suitable disc, because they have no existence in our room. They are, in fact, manufactured in our ears as difference tones, and as harmonics of the difference tones, and we " hear " them reasonably well. Then why, with such loud-speakers, can we not hear also the drums and the cymbals? It is because, as already stated, these instruments have no higher harmonics to speak of, (the overtones being mostly inharmonic upper partials), with the result that the loud-speakers produce nothing which can re-create the low fundamental tones for us in our ears. In fact, any subjective tones there are sound like noise.

23. *Subjective phenomena generally.*

Subjective phenomena suggest several other points of interest, such as the following:—Firstly, their effects are so very marked and obviously important that telephone engineers must allow for them in calculating allowable distortions. Secondly, every individual, with his particular ear shapes and resonances, must have his own personal and quite individual and exclusive perception of speech and of any piece of music; and his own variations of perception with variations of intensity. Thirdly, whistles to give two tones are made, each tone with a separate orifice. In one example they were of frequencies 850 and 1050 C.P.S. With either orifice closed, the tone from the other is rather high and feeble; but with both open we get in the ear a powerful difference tone of 200 C.P.S., the total result being very loud. The effect is a noise, and is not musical, because 850 and 1050 C.P.S. are not harmonics of 200 and do not constitute a musical chord with it.

LIMITS OF PERCEPTION AND PERCEPTIBLE DIFFERENCES.

In this section the paper gives some definite average values for the dimensions of the sensations produced in the brain by various measured intensities of sound power in the ear. The curves of Fig. 13 show these figures graphically for several important types of perception of sound. For

PERCEPTION CONTOURS.

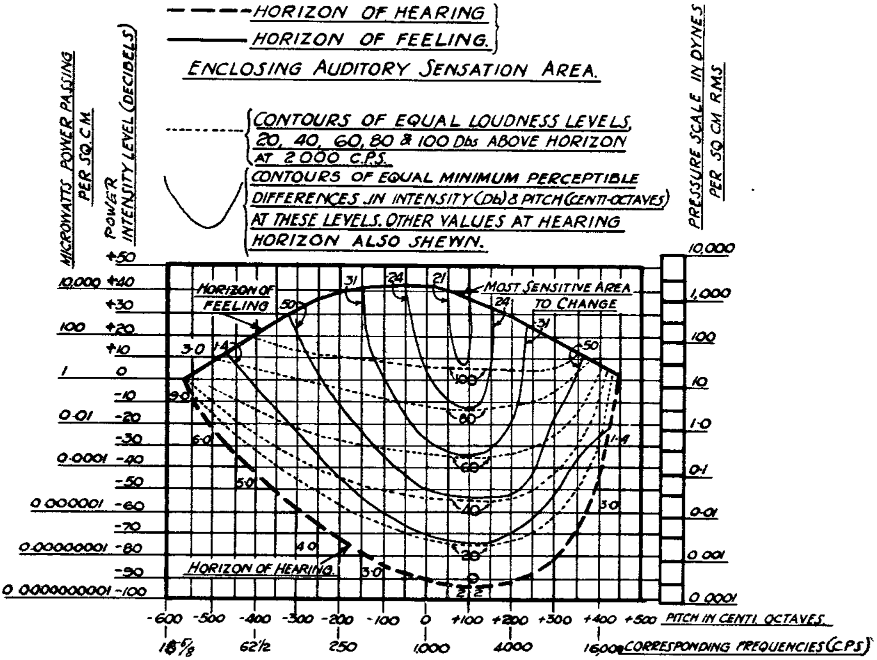


FIG. 13.

ready comparison, these curves are drawn as contour lines—that is, as lines of equal perception value. They correspond to a base line which represents the whole range of audible frequencies. Part of this figure is adapted from figures given in Mr. Harvey Fletcher's "Speech and Hearing," (by permission of Messrs. D. van Nostrand Corporation and Messrs. Macmillan). Paras. 24 to 27 describe the different types of perception covered.

24. *The horizons (or thresholds) of hearing and feeling.*

These are the values of power intensity at different frequencies at which (*a*) we can just commence to hear—a fairly definite first step; and (*b*) at which the hearing has become painfully loud and is more akin to feeling. These contours are given by the lower and upper enclosing curves of Fig. 13. The area thus enclosed is known as the "auditory sensation area." No combination of frequency and intensity outside it is audible.

It will be seen that the ear can hear very faint sounds most readily when they are of a frequency of about 2,000 C.P.S. At the extreme frequencies of about 20 and 20,000 C.P.S., the power intensity found just audible at 2,000 C.P.S. must now be multiplied by several thousand million before it becomes audible. But even now it only represents a power intensity of about 1 micro-watt per sq. cm. or an R.M.S. pressure of about 20 dynes per sq. cm. At 2,000 C.P.S. the minimum audible power is almost incredibly small, and the ear's bias against low-powered low-pitched notes can be clearly seen.

The feeling threshold curve shows a much smaller variation with frequency. A maximum comfortably audible power is reached at about 1,000 C.P.S. At higher intensity levels still, say 10,000 dynes per sq. cm. R.M.S., equivalent to a variation of atmospheric pressure of only 1%, the ear may be severely damaged.

25. *Sensation levels.*

As described at the end of Para. 7, it is often found most convenient to state the intensity level of a sound as being so many decibels above the minimum intensity level which gives audible sounds at the frequency in question. As this means above the hearing horizon just described, it follows that, if this threshold curve be raised 20 or 40 etc. dbs. (so far as it will be within the auditory sensation area), it will then give the contour line of the 20 or 40 etc. db sensation level. So these contours are omitted from Fig. 13 for clearness. They do not represent *measured perceptions*,—they are assumptions made from a single threshold perception measurement at each frequency.

26. *Loudness.*

The dotted curves · · · · · of Fig. 13 show, for all frequencies, the contour lines of the power intensity levels of different pure tones which all appear to our sense of hearing to be equally as loud as sounds of 2,000 C.P.S. which are in turn 20, 40, 60, 80 and 100 db above the threshold intensity for 2,000 C.P.S.

"Loudness" is a mysterious mental conception, as we do not know exactly how the properties in one sound combine together to make that sound seem louder or softer than the compounded properties of another sound. It is not merely pressure, or amplitude or power. We generally measure the loudness of single or complex tones against a 1,000 cycle tone, and we often find that two contrasted tones, which sound equally loud at one level of power or sensation, do not sound equally loud when we double either the power level or the sensation level of both tones.

It is interesting to note how comparatively flat is the 100 db loudness contour line, showing that the ear is much more uniformly sensitive to sounds of a given power, but of different frequencies, if this power be high. The varying slopes of these loudness contours show how important is the actual intensity level at the ear of all complex sounds; and show one reason why music heard very loudly sounds much richer in the bass than the same music heard much more softly.

27. *Sensitivity to change of intensity or pitch, i.e., "change sensitivity."*

The contour curves U of Fig. 13 show, for various frequencies and intensities, some typical values for the minimum perceptible *changes* of intensity level in decibels, and also *changes* of pitch, (*i.e.,* frequency level), in centi-octaves. Pitch changes can be included because the choice of these particular units led to the measurement *numbers* of the minimum perceptible changes of two such entirely different qualities being almost identical at any point in the area concerned. The greatest "change sensitivity" is given by the smallest number, .21. This applies to the area near 1,600 C.P.S. frequency and the very loud intensity level + 10 to + 40 db. The other "change sensitivity" contour lines are given at .24, .31, .50 and 1.4 (db or c-O), because these contours correspond to sensation and loudness levels of 80. 60, 40 and 20 db at frequencies of 2,000 C.P.S. At audible threshold levels the change sensitivity is lower than at higher intensities. We therefore get higher "change" figures, which run from about two to as much as nine at minimum audible frequencies.

It will be seen that the greater the power intensity, the less flat are the change sensitivity contour lines, *i.e.*, the greater are the variations of change sensitivity with change of frequency. This is the exact opposite to what we found in Para. 26 above for sensitivity to loudness.

Now .21 db represents a change of power of little over 5%; and .21 c-O a change of frequency of only a little over 0.1%. These very low values will give some idea of the hundreds of thousands of different pure tones in which the average ear can distinguish a difference in either frequency or intensity.

PERCEPTION WITH VARYING LOUDNESS AND DISTORTION.

Fig. 14 has been drawn to show the variations of what we may call " Perception efficiency " with changes in loud-

RELATIVE DISTORTION EFFECTS.

EFFICIENCY OF SPEECH PERCEPTION WITH VARYING TRANSMISSION CONDITIONS.

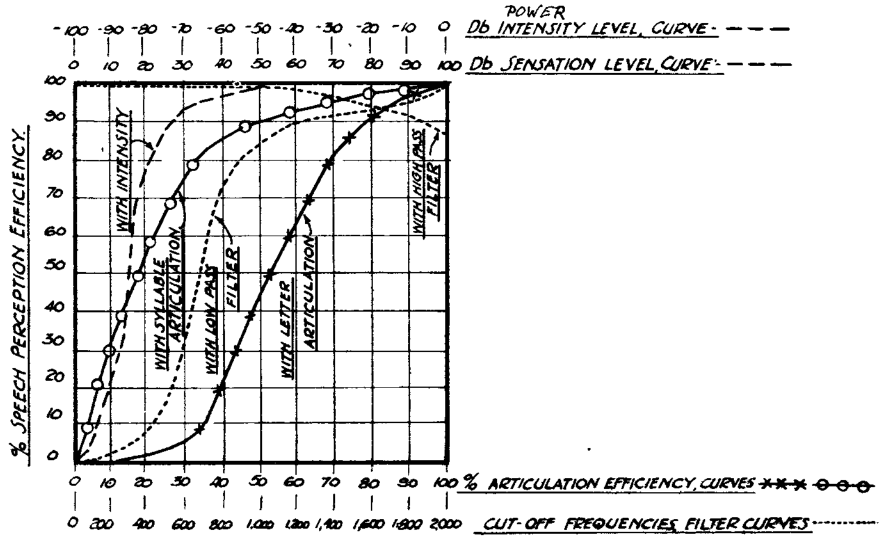


FIG. 14.

ness and in quality of transmission. Experiments on sentences can show us most readily two different efficiencies:—(1) the intelligibility efficiency, which shows the percentage of carefully selected unknown sentences which can be understood under certain given conditions, compared to the percentage under perfect conditions. In this test the hearer can have the sentences read once as slowly as he wishes. And (2) the speed of recognition efficiency, which shows the percentage of similar sentences which can be understood in a given time under similar conditions to (1), compared to the number under perfect conditions. Here any required repetitions can be obtained, or questions asked. The essence of this test is speed of understanding. We can regard "perception efficiency" as the average of these two efficiencies. It is a practical quality, which is used in this sense throughout this section of the paper.

28. *Perception efficiency and loudness level.*

Curve - - - - - of Fig. 14 shows how the efficiency of perception varies with the power intensity level or the sensation level. It will be seen that 90% is reached at the low power intensity level of −73 db and that we get 100% efficiency at about −45 db and above. If carried to very loud intensities, beyond the limits of the curve, the efficiency would again fall.

29. *Perception efficiency and noise.*

The deafening effect of noise depends largely on its loudness and frequency, and also on whether the noise occurs in the ear or ears with which we are listening, or, say when telephoning, only in the ear with which we are not listening. In practice this last condition is seldom encountered, but experiments show that considerable noise can reach the idle ear *alone* without much affecting the recognition of sounds by the other ear. It is very difficult, however, completely to screen the active ear alone, for the bones of the head carry sound waves very effectively.

Strong low-pitched tones mask considerable sensation areas, because of subjective harmonics set up in the ear. Ordinary street noises are of fairly well-mixed frequencies, and in most towns may well be at a sensation level of 20 db, and in noisy streets at as much as 40 db. Their effect on perception efficiency can readily be gauged from Fig. 14. When, for example, we are listening to speech at some particular sensation level, we simply have to read the perception efficiency figure corresponding to that intensity level lowered by 20 (or 40) db. Thus, if the speech intensity level were -55 db, the efficiency of perception with 20 and 40 db noises would be reduced to about 87% and 10% respectively. The latter fall would be very serious and would necessitate the speaker using 100 times the power to get to even 90% efficiency.

Line and other noises on telephone circuits can be measured for their sensation effect and treated in the same way. A typewriter not far away may give a noise sensation level of 45 decibels, with a corresponding masking effect. A high-pitched whistle of much higher intensity may not lower reception to the same extent, unless excessively loud, because it does not seriously disturb those areas of the basilar membrane which are most useful in listening to speech.

Many kinds of deafness are equivalent to the constant presence of external noises, and can be measured in similar terms. People who are only slightly deaf will be conscious of deafness only in really quiet localities. The reduction of noise is a very real necessity of modern life, and would be equivalent to removing a species of deafness (not to mention real discomfort) from all but the very deaf. As an example of the effect of noise, the range of hearing loud speech is reduced from, perhaps, 100 yards in very good conditions, to only a very few yards in a noisy office; to only a few feet in a noisy train; and to nothing at all in many workshops.

30. *Perception efficiency and loss of frequencies.*

The dotted curves · · · · of Fig. 14 show the efficiency of perception when there is a filtering effect in the transmission system, which completely cuts off all frequencies which are either below the cut-off frequency (a High Pass Filter), or else above it, (a Low Pass Filter). These two curves cross at a frequency of about 1,600 C.P.S., at which point, for each, we get a perception efficiency of about 94%. This is a very striking result, giving us 1,600 C.P.S. as the mean frequency for perception. But though reasonably intelligible, the speech in each case would be unnatural and unpleasant. Most of its distinctive timbre and expressive qualities would be lost.

A matter of great importance in transmission and reproduction is the fraction of power retained by waves when they are variously filtered. To return to the 1,600 C.P.S. cut-off waves, the low pass filtered wave retains about 90% of its energy. But the high pass filtered wave, which we have seen to be reasonably intelligible, though unpleasantly distorted, only retains 10% of its energy. This is because the powerful fundamental is lost. With a limit of power in any reproducer we shall hear speech most loudly and clearly when quite a wide band of low frequencies has previously been filtered out.

At normal loudness we get high and low pass filtered waves of equal power at a cut-off of about 400 C.P.S. At this cut-off the curves show that the low pass wave is almost completely unintelligible—say 8% efficiency; but the high pass wave is almost 100% effective. When speech is thus filtered to the extent of 50% on an energy basis, we have an exact parallel with a line of print. With the top half alone covered up, a line of print is almost unintelligible; but with the bottom half alone covered up, reading is very little affected.

31. *Perception efficiency and articulation.*

It is not possible to measure directly the "perception efficiency" of sentences under varying conditions, and it is tedious to do it by averaging in the way above described. With a trained staff it is usual to measure "syllable articulation." A very large number of syllables are taken, some not occurring in words at all, and are spoken one every three seconds in carefully selected groups. The articulation is the percentage of correct results under the special conditions, compared to the percentage under perfect conditions. Curve o—o—o of Fig. 14 shows how to connect syllable articulation results with perception efficiency, and thus also with the other curves given.

If it is necessary to make improvised tests with untrained men, it is better to measure "letter articulation." We proceed just as above, except that in place of syllables we use different vowels placed between particular consonants, or similar pairs; and different consonants before a particular vowel, or similar vowels. This method is slower and is less sure and less trustworthy. It gives us results which compare with perception efficiency in the way shown by curve x—x—x—x Fig. 14. This curve enables these results to be linked also with the other curves.

This section is only intended to give a very broad idea of the effects of loudness and distortion on perception; and of some ways of measuring them. Full information and detailed methods are given in the excellent publications listed in the introduction.

MODERN DEVELOPMENTS.

32. *Improvements in reproduction.*

Studies of the facts and theories above referred to, and of many others, have led to very great progress in recent years in transmission by telephone and "wireless," and in the recording and reproduction of sound by gramophones and by various kinds of electric reproducers. The telephony and wireless aspects have been very fully dealt with in the publications mentioned in the introduction and in other works, and also in the technical press. Readers may not be so familiar with progress in gramophones and electrical reproducers.

Fig. 15 gives some figures for this progress. In the lower figure is shown the first great step,—electrical in place of mechanical recording. The bottom cut-off has been

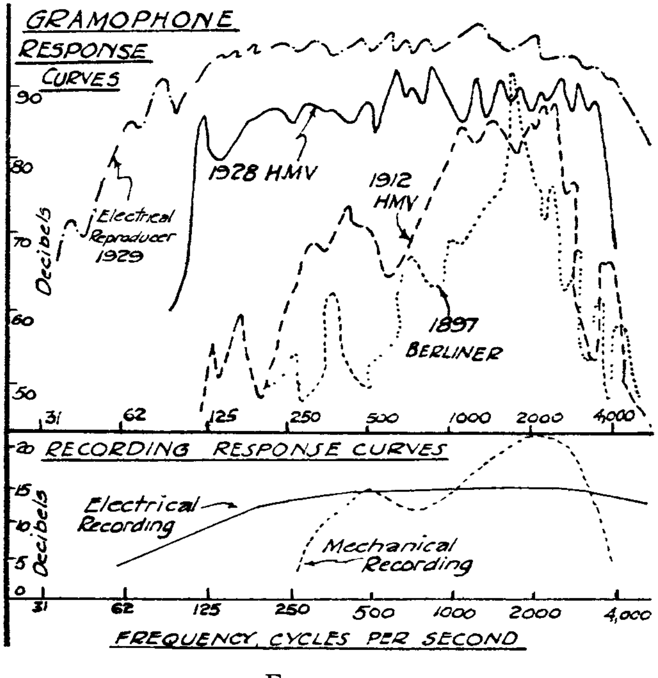


FIG. 15.

lowered from about 250 to about 60 C.P.S., and the top appreciably raised. Further, the new curve is flat topped. The records are therefore very much better than of old, though there is still heavy falling off at low frequencies, due mainly to the narrow width to which the groove must be limited.

As regards reproduction, the upper part of the figure shows (in part by the courtesy of The Gramophone Co., Ltd.) response curves in decibels for (1) An 1897 Berliner Gramophone, (2) A 1912 H.M.V. Gramophone, (3) An infinitely better 1928 H.M.V. Gramophone, with exponential horn. Here we have an excellent response over a wide range of frequencies. The " response " is shown with respect to the original sound, and so includes both recording and reproducing distortions. An 8 ft. horn was necessary to get down to the 100 C.P.S. To get still further down, say to 57 or 58 C.P.S., a horn 15 ft. long would be necessary. But a mechanical gramophone would not then have enough power to give suitable loudness to the whole range, because so much would be absorbed by the low notes. So Fig. 15 shows what must be nearly its limit of possible response. And (4) we have the really wonderful response of an electrical reproducer. This electrical system has all the additional advantages of a very wide over-all volume control, and a wide range of loudness at any over-all volume. In fact, electrical improvements, on telephone engineering lines, have revolutionised the recording and reproduction of sound.

33. *Speech efficiency testing by machines.*

In view of all the subjective and noise effects above described, it is not surprising that telephone engineers have developed means of testing transmitters and receivers, by the use of which the only human judgment required is to take a voltmeter reading. At least it is hoped that further experience will make it as simple as it sounds. If so, it will prove a great boon, particularly in routine testing, where thousands of instruments are involved. For not only are ears notoriously variable, (as well as being of all sorts of shapes and sizes), but concentration for long periods at the receiving end is almost impossible except for trained experts.

The source of sound used is a rhythmic oscillator with a rhythm of about 5 per sec. between frequencies of 600 and 1,600 C.P.S. It is much improved if a frequency of about 180 be superposed and subsequently filtered out. Microphone outputs are measured directly by a Valve Voltmeter. Receivers have fitted to them a dummy ear combined with a suitable transmitter. From this latter, a valve voltmeter will give visible readings of the efficiency of the receiver. Thus many uncertain factors in sound measurements are eliminated.

Reference should be made to publications of the work of Capt. B. S. Cohen, Mr. A. Hudson, and Mr. Harvey Fletcher and others, for recent work on machine testing, and on " testing standards."

34. *Conclusion.*

This paper has been written to draw attention to many points of general interest in the dual phenomenon of sound and hearing, and in particular to some of the problems which beset engineers who attempt to transmit and reproduce sound. It has given some indication of the rapid strides towards perfection, which have recently been made, and some evidence of the ever growing utility of reproduced sounds in our every-day life. The almost incredible sensitivity and range of the ear have been described and the great practical importance of its subjective phenomena has been emphasised.

Reference may perhaps be made, in conclusion, to a fundamental distinction between the sense of hearing in mankind and all other senses. A man possesses by nature, as a corollary to his sense of hearing, the wonderful power of speech—a delicate, flexible and mentally delightful stimulus to the hearing of his fellow men. The gift of accurate hearing, coupled with the power of speech—a unique combination of natural sense and *natural* stimulus—has been an outstanding factor in human progress. The extension of the range of speech from only a few yards to thousands of miles must surely accelerate this progress.

APPENDIX.

Some Important Properties of Sound.

1. *The nature of sound.*

Hearing is a primary sensation. This sensation is stimulated by suitable vibrations of the air in our outer ears; or occasionally directly through the bones of the head. This stimulus to hearing we call "sound." Chronologically we have first a material substance called the source of sound, which is able to vibrate in a material medium. The process starts when this material substance or source is compelled to vibrate rapidly. Similar vibrations are at once passed on to the material medium, and in that medium a train of sound waves is set up. Next, the sound waves reach our ears, which contain a mechanism for converting these sound waves into nerve impulses. The impulses thus produced are then transmitted by the nerve fibres to the brain; and there, finally, we get a more or less accurate mental perception of the original sound.

2. *The source of sound.*

The source of sound may be a taut string or a tuning fork, either of which we can see or feel vibrating; or it may be a column of air, as in an organ pipe; or, perhaps, a telephone receiver diaphragm, or a thousand other things, provided that they are suitably vibrating. Energy is needed to start such vibrations. Such a vibration is well illustrated, in slow motion, by the swing of a pendulum bob on a string. The number of complete (or double) swings per second, usually termed the number of cycles per second, (C.P.S.), is called the frequency. This frequency of vibration must be roughly between 16 (or 20) and 16,000 (or 20,000) cycles per second to produce audible sounds. Sources of low and high frequency give sounds which are low-pitched and high-pitched respectively. The distance travelled in a single swing either backwards or forwards from the central, or rest, position is called the amplitude. It is a quarter of the total movement per cycle. The greater the amplitude of swing, the louder the sound. Incredibly small amplitudes will give audible sounds; a minute fraction of one thousandth of an inch is sufficient.

3. *The medium.*

The vibrations of the source of sound are transmitted to the medium in which the source vibrates. This medium must be a material medium. The ether is not sufficient. The process resembles a luggage train shunting backwards and forwards several times a few feet at a time. The engine alternately bumps and pulls the truck next to it, which does the same to the truck next to it, and so on. A succession of first a bump, then a pull, then a bump, and so on, is passed right to the far end of the train. Each truck merely goes backwards and forwards, backwards and forwards, and the only things which travel along are the bumps and the pulls. These bumps and pulls, in series, always travelling outwards from the engine, carry with them what is left of the energy exerted by the engine. The heavier the trucks are, the more will be the load on the engine; and the longer the train is, the weaker will be the bumps and the pulls which reach the trucks at the far end.

4. *The formation of sound waves.*

Here is a fairly close analogy with what happens when we have a source of sound in place of the engine, and particles of air instead of the trucks. The bumps cause compressions, or condensations, of the air particles; the pulls, caused by a progressive vacuum effect, give us areas of reduced pressure, called rarefactions. A succession of alternate condensations (bumps) and rarefactions (pulls) passes outwards from the source and gives us our series, or train, of sound waves. These alternate condensations and rarefactions carry away the kinetic energy of the source, and provide a load upon it. The bigger the source is, the greater will be the volume of air which is set in vibration at the same amplitude as the source, and the heavier therefore will be the loading. The braking effect of this loading of the source is called damping. Unless further energy be supplied to the source, this damping will steadily reduce the amplitude of the vibrations of the source, and finally will stop them completely. Whilst this is happening, the initial vibrations of the air particles adjacent to the source will become smaller and smaller in amplitude; and when the source comes to rest, no more waves will be added to the train. But the condensations and rarefactions already started outwards will of course continue their journey.

5. *The attenuation of sound waves.*

Let us return to the strong initial air vibrations absorbed from the source. In the open air, quite differently from the luggage train, these vibrations in the medium will normally spread outwards in straight lines in every direction. Instead of the waves passing along a single straight line, and so having a wave front like a point, we shall have a more or less spherical wave front. There will again be no permanent transfer of matter, but individual air particles will vibrate backwards and forwards, backwards and forwards in harmonic motion along one of many radial straight lines. Obviously the area of wave front will expand greatly as the waves travel outwards. As the area covered by any original parcel of energy thus expands, its intensity of power, that is its power per square foot of surface, must obviously decrease. This means a diminishing amplitude of particle vibration, the further the wave is from the source, quite irrespective of any wastage of energy en route. This attenuation, as it is called, is hastened by energy being dissipated firstly in heat, owing to the jostling of the air particles, and secondly in causing various obstacles to vibrate; still further loss occurs each time the waves are passed on from one medium to another, as for example from the air of a room to a door, and then from the door to the air beyond it. Far enough away from the source, therefore, the amplitude gets so small that the waves become inaudible and can be considered to have died away. But note that the frequency keeps constant to the end.

6. *Time and distance limits for sound waves.*

The total result of the process above described is that sound waves, as such, can only penetrate quite short distances; and their life is measured in seconds at the most. And these waves, which represent a continual stream of energy, cannot as such be held in suspense, as it were, and released at will. So sound waves proper are seriously restricted as to both time and distance. For long distance transmission of sound, or for its storage, telephone and gramophone engineers are needed.

7. *The velocity of sound.*

With sound waves we have two quite different velocities to consider. What we call the velocity of sound is the transitional velocity of the energy-bearing train of rarefactions and condensations already described. Normally, in air, this velocity of sound is about one fifth of a mile per second, roughly a million times as slow as light. In water it is about 1 mile, and in solids 2 or 3 miles, per second. There is also the average backwards and forwards velocity of the individual air particles. For any given frequency it is clear that the greater the amplitude, the greater will be the mean particle velocity. This fact is used to make important sound measurements with the Rayleigh Disc.

8. *A moving source of sound.*

The velocity of sound waves in air is independent, not only of the frequency and amplitude, but also of any bodily transitional movement of the source itself through the air. But if the source is rushing towards the hearer, as in the case of an express train approaching a country station, each successive condensation and rarefaction has a shorter distance to travel than the one before. These condensations and rarefactions will consequently arrive more closely together than if the source were stationary. The resulting higher frequency gives a higher pitched sound. Conversely, a rapidly receding source gives a lower pitched sound. So if the engine whistles a steady note as it rushes through the station, a listener on the platform will hear its note fall suddenly as the engine passes him.

9. *Reflection and diffraction.*

Sound is reflected from a large surface, like light from a mirror, and produces echo effects. The idea that " sound rises " is due to reflection from the ground. Every sound heard is a mixture of the original wave and of waves reflected from surrounding walls and objects of all kinds. Sometimes rooms and halls, etc., have very bad acoustic properties because every sound in them persists too long. This is caused by the echo being repeated backwards and forwards due to lack of absorption by the walls. Another property of sound waves is that they can pass round corners. This is due to a diffraction effect, as it is called. Diffraction round the head causes a difference between the sounds reaching the two ears, and helps us to locate sounds. Ripples on a pool, on which large and small objects are floating, illustrate reflection from large objects and diffraction round small ones. Reflection may be used to focus sound waves into a beam, like a concentrated beam of light.

10. *Resonance.*

We must now consider resonance. It can be shown that any body has a natural frequency of vibration—sometimes two or more. This natural frequency depends on the body's size and shape, and so on. The body vibrates very readily at this frequency, but not readily at others. This is very easily demonstrated with a string-hung pendulum, for at any place the natural frequency of such a pendulum depends on its length alone. We get resonance if we give the pendulum a series of taps at the same frequency as its own exclusive natural frequency. Minute taps so timed will then soon produce large swings, because every tap helps the movement and in no way impedes it. That is the essence of resonance. There will naturally be times when the frequency of any sound wave happens to be identical with the natural frequency of some obstacle, which it encounters. Here again we have resonance, the received and natural frequencies being identical. The transfer of energy from the source to the body is then very rapid and efficient. This is what causes some ornament or candlestick to rattle when some particular note is played on a piano.

11. *Resonance in practice.*

Resonance is of the greatest practical importance. Most wind instruments, for example, are based on the fact that open-ended tubes have lower resonant frequencies the longer they are. In the case of an organ, an air current is forced on to a sharp edge and is thereby caused to vibrate with a wide range of frequencies. This vibrating air is then admitted to a pipe of a given length, with a corresponding natural frequency, and sounds of this exclusive frequency are enormously magnified and the other frequencies dissipated. This is not done by adding selective external energy, but by making the loading and radiation of one particular frequency much more efficient and effective than that of all the others. Conversely, suppose that we suspend a light disc or diaphragm, which has a resonant frequency. If the disc does not then start vibrating at that frequency, we can be certain that the air there also is not vibrating at that frequency.

12. *Forced vibrations.*

When a body is forced to vibrate at some frequency different from its natural frequency, we get forced vibrations which tend to die away rapidly. The action is not very smooth or efficient, and the amplitude produced is less than for resonant vibrations. The easy movement of a donkey going homewards reminds one of resonant vibrations, whereas he has to be forced in any other direction. Forced vibrations are, however, much used in designing string instruments. The strings, if they alone vibrated, would move so little air at their own amplitude as to be almost inaudible. But in a 'cello, for example, really loud sounds are emitted because the strings produce forced vibrations at considerable amplitude in the 'cello body, which is of large area. This more effective radiation means heavier damping of the strings and the bow experiences greater resistance. The player, in fact, can put more effective energy into his work.

13. *Complex sounds.*

Most of the sounds around us are very complex—that is to say, they are made up of several simultaneous waves of different frequencies. Any one air particle at a given instant will move in one direction only, of course, and at one velocity. But it will be subject to a periodic motion which will be compounded of several simple harmonic motions. We can get an idea of such a movement in slow motion by watching the swinging of the bob of a pendulum, which is itself suspended from the swinging bob of another pendulum. In the case of musical instruments and voices, what we regard as single pure tones are actually complex sounds composed of a fundamental and several overtones. These overtones are usually harmonics of that fundamental. Frequencies of 100, 200 and 300, for example, give a harmonic series of 100 as fundamental, and 200 and 300 as second and third harmonics. Each harmonic frequency is a simple multiple of the fundamental frequency and has its own characteristic amplitude and damping. These harmonics depend on the physical properties of the particular instrument and originate in natural resonance. The overtones of percussion instruments, however, are mostly inharmonic upper partials and are of a transient nature. Complex though even simple notes are thus seen to be, far more complex are the ordinary sounds which reach our ears. For these are a compound of sounds of several different fundamental frequencies, each with its characteristic pattern of overtones, and each varying from the other in loudness, duration and phase. Further, each is reflected differently from our surroundings.

14. *Interference or beats.*

If a complex sound wave contains two component waves of nearly equal frequency, these two waves interfere with each other's effects. At some particular point in space, at some particular instant, they may perhaps act together and add their amplitudes to a particle of matter, so as possibly to double its normal amplitude. Then the two component waves, being of different frequencies, gradually get out of phase at this point, and a moment later their effects will clash and more or less cancel each other out, and hold this same particle almost stationary. The result is a waxing and waning of the loudness of the sound, known as beats. The perception of beats in the ear means inevitably the presence in the ear of two simultaneous waves of adjacent frequencies, but we must recognise the possibility that one of these component waves may in some way or other be mechanically produced in the ear itself, and may not be present in the air—that is in the stimulating sound wave. This latter point can be settled definitely in each case by the resonant disc method mentioned in para. 11, above.

15. *Octaves and decibels.*

We must briefly consider two aspects of the mental perception which sound waves produce—pitch and loudness. The higher the frequency of a note, the higher does the pitch appear to the ear; and the greater the intensity of power in the wave, the louder does it sound. We measure the frequency in cycles per second (C.P.S.) and the power intensity in micro-watts (mic.w.) per sq. centimetre. How are we to measure pitch and loudness?

Take pitch first. Experiments have proved that, if we have three notes of frequencies, 500, 1,000 and 2,000 C.P.S., the brain senses the same difference in pitch between the notes of 500 and 1,000 C.P.S. as it does between those of 1,000 and 2,000 C.P.S. In fact to the brain it is always the *ratio* of one frequency to another that counts, never the difference in C.P.S. We obtain a measure of pitch by giving the name " octave " to the *step in frequency* from any value whatever to double (or half) that value. An octave is thus a frequency ratio of 2 to 1. A centi-octave is a step of a ratio such that 100 successive steps, each in this same *ratio,* will give an over-all frequency step or ratio of one octave, *i.e.*, of 2 to 1. Mathematics show that a c-O is a ratio of 1.007 to 1 ; or, if we prefer it, a .7% increase.

It is convenient to take 1,000 C.P.S. as a reference level of frequency. Higher notes are + so many c-Os in *level* of frequency; lower pitched notes − so many c-Os. + 1 c-O will mean 1,007 C.P.S.; −100 c-Os gives 500 C.P.S. We thus have a scale by which we can measure pitch. The pitch of a note can now be accurately defined as so many centi-octaves above or below our arbitrary reference level of 1,000 C.P.S., which is also called zero level. Zero *level* on such a scale does not of course mean a frequency of no C.P.S. This scale has the great advantage that every step in it is equally significant and important as regards mental perception. (Please see the horizontal scales of Fig. 13).

We have similar conditions in our perception of loudness with respect to power intensity. If we have three sounds of power intensities, .1, 1 and 10 micro-watts (mic.w.) per sq. cm., the 10 mic.w. sound is sensed to be just as much louder than 1 mic.w., as the 1 mic.w. sound is than the .1 mic.w. To this particular power intensity ratio of 10 to 1, we give the little used name of 1 Bell; but in practice it is always called 10 decibels (db), as the Bell is too large a ratio for convenience. We find that 1 db is nothing more than a power intensity ratio of 1.259 to 1 ; or we can say that there is a difference of 1 db in the power intensity level of two sounds when the one contains 25.9% more power than the other.

It is convenient to take 1 mic.w. per sq. cm. as our reference level, or zero level, of power intensity. +1 db will mean a power intensity of 1.259 mic.w. per sq. cm.; +3 db will mean 2 (almost); $+(x \times 10)$ db means 10^x; −20 db = .01 (mic.w. per sq. cm. in each case). Notice the scales on the left of Fig. 13. We can well repeat that a step-up of 1 db means a 25.9% increase in power intensity,—or possibly in some similar property. It gives a power amplification in the ratio 1.259 to 1. Expressed as a loss, 1 db means a power attenuation in this same ratio, which equals 1 to 0.794. Thus a circuit of 79.4% efficiency gives a power loss of 20.6%, shown as −1 db.

Power amplification (or attenuation) factors can be converted to decibels gain (or loss) as shown below.

Amplification (or attenuation) Factor.		Decibels rise (or fall) approx.	
Actual.	Equivalent.	How derived.	Actual.
2	2	3	3
4	2^2	3×2	6
8	2^3	3×3	9
10	10	10	10
20	10×2	10×3	13
80,000	$10^4 \times 2^3$	$(10 \times 4) + (3 \times 3)$	49
500,000	$10^6 \div 2$	$(10 \times 6) - 3$	57

The shapes of " sound and hearing " curves give a true mental picture only when they are based on octaves and decibels. If plain C.P.S. and power scales be used, the various rises and falls of frequency and power depicted are relatively misleading.

Birch and Whittington, Printers, Epsom, Surrey