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Scientific Research Applied to the Telephone Transmitter and Receiver *

By EDWIN H. COLPITTS

LET us recall a scene at the Centennial Exhibition in Philadelphia in 1876. Across a room had been strung wires connecting crude instruments, at one end of the room a transmitter and at the other end of the room a receiver. Dom Pedro, Emperor of Brazil, takes up the receiver and listens while Alexander Graham Bell speaks into the transmitter. The Emperor, astonished at hearing Mr. Bell's voice in the receiver, exclaims in amazement, "My God, it talks."

When at the same place, Sir William Thomson (later Lord Kelvin) took up the receiver and listened to Mr. Bell, the words of this distinguished scientist were, "It does speak," and continuing, "it is the most wonderful thing I have seen in America."

Sixty years have passed and, as a result of continued effort, the use of the telephone has become such an everyday matter that even the ability to talk from Tokyo in your country to New York in my country scarcely excites comment or wonder. It is not surprising that, to the layman, the element of distance seems the most striking factor in the technical development of the telephone art. As a matter of fact, while the conquest of distance has involved much scientific effort, and very ingenious and highly developed methods for the transmission of speech currents, the magic of the telephone still resides in the instruments which provide for the conversion of mechanical energy, namely speech sounds of highly complex wave form, into electrical currents of corresponding wave form, and the reverse process of converting these electrical currents into speech sounds. These instruments, the transmitter and the receiver, are basic to the whole telephone art. As they have been improved by development and design, it has become possible not only to render a higher grade of service but to effect economies in other portions of the plant. For example, the

* Another of three Iwadare Foundation lectures delivered during this past spring in Japan by Dr. Colpitts. One lecture was published in the April 1937 issue of this *Journal*.

very extensive use of fine-gauge cables in the plant of the Bell System was, to a large extent, made possible by the development of more efficient transmitters and receivers. Further perfecting of these instruments promises additional improvements in service and some further economies.

Telephony, restricting the term to ordinary two-way talking between individuals, involves an element not present in any other service. It does not greatly concern one customer of an electric light or power company whether another customer chooses to use inadequate or inefficient or poorly located lamps or other equipment. That is, each user of the service is, under any ordinary conditions, independent of all other users. In the case of telephony, however, the problem is entirely different; for one user of the telephone is greatly concerned with not only the apparatus furnished to any one with whom he has occasion to talk but also with other factors affecting the use of this apparatus, such as the amount of noise in the room where the apparatus is located, the user's habits of speech, and whether his ability to hear is normal. Telephone instrumentalities must therefore be so designed and the plant so engineered as to meet reasonably wide variations from what may be termed normal conditions, and ratings of performance should be similarly established.

I believe telephony in your country as in ours will find an increasingly wide field of service, and there is no single factor more important to a sound development of this art than the subscriber apparatus. With your permission, therefore, I will broadly outline certain work of the Bell Telephone Laboratories which has had a very direct bearing on these telephone instrumentalities and the form they are likely to assume. I will first discuss the research program which has been carried on in these laboratories, and then indicate to you the general trend which development and design have taken.

The research program basic to the development and design of transmission instruments has itself been a matter of development as a better understanding of the problems unfolded and as the need for research in this or that direction became apparent. The research problem basic to the development and design of transmission instruments may be described as having the following very broad scope: an understanding of their physical operation viewed as electromechanical structures; an understanding of speech mechanism and an accurate physical definition of speech air waves; an understanding of the hearing processes and a determination of how hearing is affected by factors present in telephony. Also, our research program may be said to have included research upon certain materials, the results of which have an important bearing either upon an understanding of the operation of these instruments or upon their practical design. In addition to the development of many methods of measurement and testing applicable to laboratory research and development, of very great importance has been a development of the testing methods which permit of a better final evaluation of the developments based upon the results of this activity.

Instruments as Electromechanical Structures

The telephone transmitter itself is a complex mechanical and electrical structure. Its general method of operation can be described qualitatively in relatively simple terms, but the operation of few structures is more difficult to define in definite quantitative terms and relationships. For example, we are concerned with acoustical problems such as those involved in the air connection between the lips of the speaker and the diaphragm of the instrument. This air connection may involve a short column of air as in those instruments which have a telephone mouthpiece. Connection between the column of air and the working parts of the transmitter may be partially closed by a perforated section. When we come to consider the operation of the instrument itself, there is involved the mechanical vibration of the diaphragm as it operates on the carbon, and further, the whole question of electric conduction in the small mass of granular carbon itself.

In the case of the receiver which converts telephonic currents into speech sounds, we have very similar acoustical, mechanical and electrical problems with the exception, of course, of the mechanical and electrical problems introduced by the carbon of the transmitter.

A large amount of research work has been carried on in the Laboratories relating broadly to the transmitter and the receiver as electromechanical physical structures. The theory of these devices as vibrating systems has been developed so that their overall performance can be related to the various structural features. Consequently, our development and design engineers are now enabled to predetermine by calculation how certain modifications in structure will affect the physical performance of the instrument. In other words, the design process has become very much less "cut and try."

Research has been undertaken and substantial progress has been made on a study of microphonic action in carbon. In order to develop a complete theory of the operation of the transmitter, it is necessary to understand fully what takes place between each carbon granule in the carbon chamber.

Speech Sounds

Let me outline briefly some of the results of these studies on speech. The source of any voiced sound is in the larynx. On both sides of this larynx there are two muscular ledges called the vocal cords. When we breathe, these two ledges are widely separated, but when a voiced sound is produced, they come close together, forming a long narrow slit. As they come close together, the air passing through the resulting slit is set into vibration producing a sound. It has been generally supposed that the pitch of the tone thus produced was determined by the natural frequency of vibration of the two vocal cords, and that by changing the tension of these cords, the pitch of the tone can be raised or lowered at will. As most of you know, their natural frequency of vibration is the rate that they would vibrate to and fro if they were plucked and set into vibration like a banjo string or an elastic band. Our studies revealed that the natural pitch of these cords while a tone is being produced is considerably below that of the pitch of the tone. It is true that the pitch of the tone produced is affected, somewhat, by the elasticity of the vocal cords, but it is principally controlled by the size of the air opening between them. The little plug of air between the two vocal cords vibrates through a very much larger amplitude than the amplitude of the cords themselves and is the real source of the sound. The mass of this small plug is controlled by the size of the opening and by the elastic forces pushing it to and fro—namely, the air pressures on either side of it. It is evident that these oscillating pressures will be influenced by the size and shape of the trachea leading into the lungs on one side and by the size and shape of the tongue, mouth, and nasal cavities on the other. The mechanical action involved is analogous to the electrical action in a vacuum-tube oscillator. The sound which is generated at the vocal cords is modified as it passes through the throat, mouth, and nasal passages. The real character of the sound which enables us to identify words is wholly dependent upon the manner in which this cord tone is modified by the changing sizes, shapes, and characters of these passages and the outlet to the outside air.

After the various speech sounds leave the mouth, they are transmitted to the ear of the listener by means of air vibration. As an example of the type of disturbance created in the air, consider the sentence, "Joe took Father's shoe bench out." This silly sounding sentence is chosen because it is used in our laboratories for making tests on the efficiency of telephone systems. The sentence, together with its mate, "She was waiting at my lawn," contains all the fundamental sounds in the English language that contribute appreciably toward the loudness of speech. As the sound wave produced by speaking this sentence travels along, each particle of air over which it passes executes a vibration through its original or undisturbed position. The successive positions occupied by the particle as it moves in the complicated series of vibrations corresponding to a spoken sound can be visualized in laboratory investigations from oscillographic records of the corresponding telephone currents.

Each successive particle of air along the line in which the sound is traveling executes a similar complicated series of vibrations but any particular oscillation is performed at a later instant by the particle which is farther away from the source of the sound. The disturbance in the air which represents a spoken sound may then be pictured

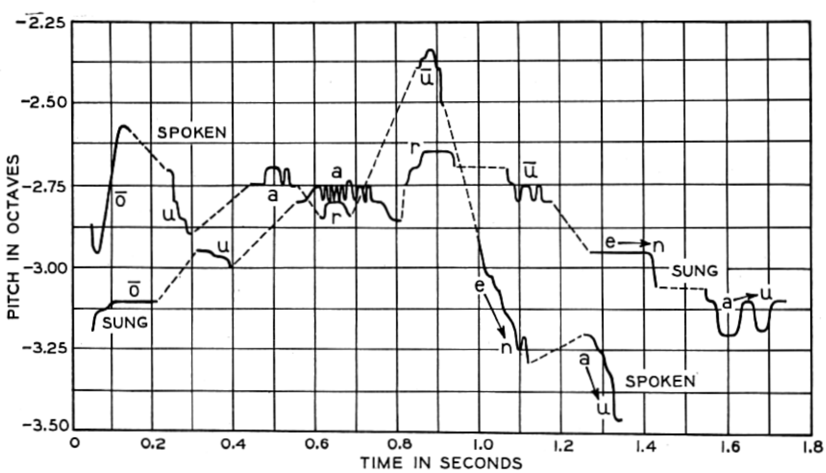

Fig. 1—Melodic curves showing the variation of pitch with time as the sentence "Joe took Father's shoe bench out" is spoken and sung.

either, as was first described, in terms of the successive positions of a single particle or in terms of the displacements at any instant of each of the particles along the line of travel of the sound wave. For example, for the sentence "Joe took Father's shoe bench out," the disturbance carrying the sound *j* in the word "Joe" is about fifteen hundred feet from the mouth by the time the sentence is finished. I have a record here which was taken in our laboratories which shows the intricate motion of each particle of air as this sentence is transmitted through the air.

If we analyze the wave when the sentence "Joe took Father's shoe bench out" is spoken, the variations in pitch of the speech sounds can be determined from the vibration rate. Such an analysis is shown in Fig. 1. The variations in pitch are represented on the vertical axis. The duration of the sounds in fractions of a second is represented on the horizontal axis. It will be seen that the pitch rises and falls as the various sounds are spoken. This representation of the pitch variation is called the fundamental melodic stream. It is the melody in the same sense as this term is used in music, although it is evident that the pitch changes do not take place in musical intervals as would be the case if the sentence were sung.

To show the contrast, a graph was made when the sentence was intoned on the musical intervals *do, re, mi, fa, mi, re, do.* An analysis of the graph gave the result shown in Fig. 1. In the case of the sung sentence the pitch changes are in definite intervals on the musical scale, while for the spoken sentence the pitch varies irregularly, depending upon the emphasis given. The pitch of the fricative and stop consonants is ignored in the musical score, and since these consonants form no part of the music, they are generally slid over, making it difficult for a listener to understand the meaning of the words. Some of our friends in the musical profession may object to this statement of the situation, but I think it will be agreed that a singer's principal aim is to produce beautiful vowel quality and to manipulate the melodic stream so as to produce emotional effects. To do this, it is necessary in singing to lengthen the vowels and to shorten and give less emphasis to the stop and fricative consonants. It is for this reason that it is more difficult to understand song than speech.

There are two secondary melodic streams of speech represented by the second and third curves from the bottom of Fig. 2, which are due to the resonances imposed upon the speech sound by the throat and mouth cavities. The numbers on these curves give the number of the harmonic which is reenforced. These two secondary melodic streams are not sensed as changes in pitch, but rather as changes in the vowel quality. Then there is a fourth stream, or, it would probably be better to say, a fourth series of interrupted sounds which are very high in pitch and are the sounds which enable us to identify the fricative consonants. The secondary melodic streams produced while speaking the same sentence are approximately the same for different persons, even for a man and a woman, while the fundamental melodic stream is usually quite different. This latter stream is not used in identifying words, but it is used sometimes to give different meanings to the same words.

As one listens to this sentence he hears the variations in loudness as well as in pitch. Loudness is related to the amplitudes and frequencies of the components of the tone, but this relationship is very complicated. It is dependent upon the action of the ear, including the nerve mechanism carrying the message to the brain. This relationship has been under study for a number of years so that we are now able to calculate from physical measurements the loudness for a typical ear and also to devise instruments for measuring approxi-

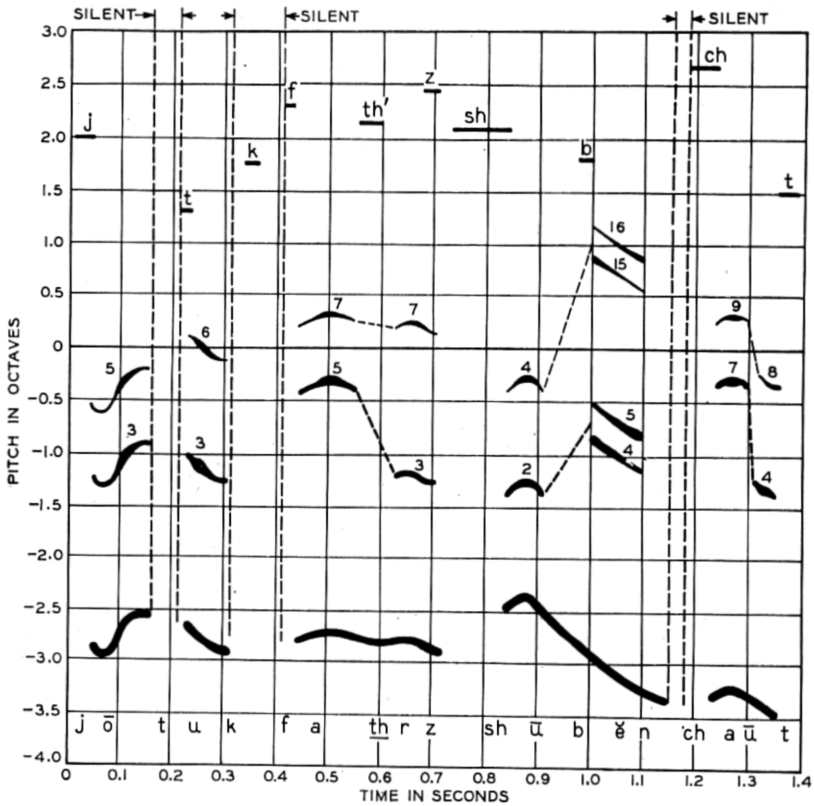

Fig. 2—Melodic curves showing the variation of pitch with time as the sentence "Joe took Father's shoe bench out" is intoned on the musical intervals do, re, mi, fa, mi, re, do. The pitch changes in regular intervals rather than in irregular intervals as shown in Fig. 1.

mately the loudness of any sound. The result of using such a device for recording the variations of loudness in the spoken sentence which we have been discussing is shown in Fig. 3. For comparison, the variations in pitch are also shown in this figure.

If the fifteen-hundred-foot wave carrying the sentence above mentioned could all be collected into an energy collector, the question arises, "How much energy would be involved?" It is not possible here to describe the devices by which we were able to measure accurately the energies and frequencies involved in speech, but the results of this research work are interesting. When this sentence is spoken fairly rapidly, it will contain about two hundred ergs of energy. About 500,000,000 ergs of energy pass through the filament of an ordinary incandescent lamp each second. This shows that the acoustic

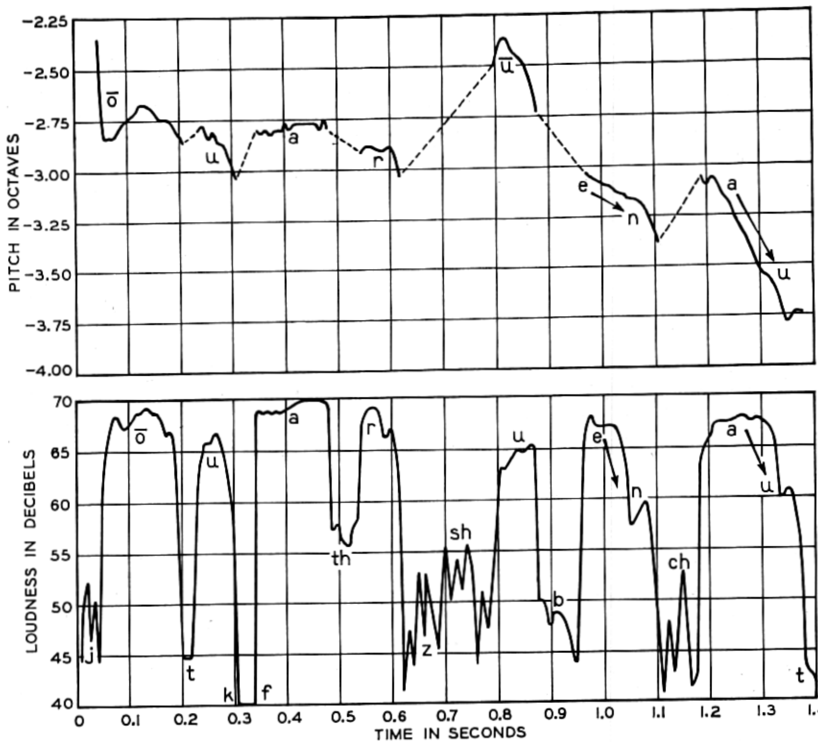

Fig. 3—Graph of the loudness of the various sound elements when the sentence "Joe took Father's shoe bench out" is spoken.

energy in this sentence is very small. Putting it in another way, it would require five hundred persons speaking this sentence continuously for a year to produce sufficient speech energy to heat a cup of tea.

An examination of the wave produced by this sentence shows that the vowels contain considerably more energy than the consonants. Exact measurements have indicated that in ordinary conversation the ratio of the intensity of the faintest speech sound, which is *th* as in "thin," to the loudest sound, which is *aw* as in "awl," is about one to five hundred. The actual power used in producing the various sounds depends, of course, upon the speaker and the emphasis with which he pronounces the sound. The power in an accented syllable is three or four times that in a similar unaccented syllable. Measurements upon a number of voices during a conversation have indicated that the average power in the speech produced is ten microwatts (one one-hundred-thousandth watt). Some speak with more and others with less than this power. In Table I is shown how various voices in a sample group vary from the average. It is seen that seven per cent speak with less than one sixteenth the average power, eighteen per cent use powers lying between one quarter and one half the average, and four per cent between four and eight times the average. No speakers were found to use more than eight times the average for conversational purposes.

TABLE I

RELATIVE SPEECH POWERS USED BY INDIVIDUALS IN CONVERSATION

Ratio of power of individual speakers to average power..	Below 1/16	1/16 to 1/8	1/8 to 1/4	1/4 to 1/2	1/2 to 1	1 to 2	2 to 4	4 to 8	Above 8
Per cent of speakers.........	7	9	14	18	22	17	9	4	0

Now let us consider the variations for a typical speaker. As a conversation proceeds, the speech power varies from zero during the silent intervals to peak values which frequently are one hundred times the average power. Extensive measurements of these peak powers upon a number of speakers indicated a distribution about the average as shown in Table II. For example, if we should examine the speech

TABLE II

PEAK POWERS IN CONVERSATIONAL SPEECH

Power Boundaries In Terms of Average Power	Per Cent of Intervals
Below 1/8	12
1/8 to 1/4	4.0
1/4 to 1/2	4.5
1/2 to 1	5.5
1 to 2	8.3
2 to 4	12.7
4 to 8	18.6
8 to 16	17.0
16 to 32	10.5
32 to 64	5.1
64 to 128	1.7
Above 128	.1

during each one-eighth-second-interval throughout a typical conversation, we should find that for seventeen per cent of them the peak power would lie between eight to sixteen times the average over a long interval. It is seen that the most frequently occurring value of the peak power is about ten times the average.

Although a typical voice of a man and a typical voice of a woman are alike in that they use the same average power and variations of power from this average, they are different in other respects which we shall now consider. It is well known that the pitch of the voice of a woman is about one octave higher than that of a man. It was not known, however, until our experiments revealed it, that the intensity of the components having vibration rates above three thousand cycles per second was definitely greater for voices from women than from men. The following investigation shows the extent of this difference.

An apparatus has been devised in our laboratory which will receive the speech during a conversation and then sort out the components into groups depending upon their intensity and pitch. Those lying in each half-octave band on the pitch scale are automatically grouped together and the group power measured. Also, by means of another automatic device, a sorting process is accomplished within the group placing together all the components having powers between certain power boundaries so that they operate a particular recording meter. It was by means of an apparatus of this latter type that the results in Table II were obtained. It was found that the powers were distributed in each of these pitch bands in approximately the same manner as indicated in Table II for speech as a whole.

The relative values of the average speech power in each of the half-octave bands are shown in Fig. 4. The horizontal positions give the pitch in octaves above or below a tone having a vibration rate of one thousand cycles per second. The vertical positions give the fraction of the total power which comes into each half-octave band. For example, consider the half-octave from − 2.25 to − 1.75, which is the octave with its midpoint at middle "C" on the musical scale. The fraction of the power coming into this half-octave is about one quarter. It will be noted that for both types of voices the maximum power occurs in the second octave below one thousand cycles. This particular octave contains about one half of the total speech power. The octaves on either side of this one containing the maximum power contain slightly less than one quarter of the total power. No other octave contains more than about three per cent of the total power. It is seen that for the band of lowest pitch the voices from men contain about eight times the power of those from women. Also, as stated above, for pitches above one—that is, for tones having vibration rates above two thousand cycles per second—the voice power for women is greater than for men. For the half-octave in the region of pitch three octaves above one thousand cycles, it is about ten times greater.

For some reason which is not very evident, women use higher pitch sounds for producing the fricative consonants, and this results in the greater power shown in the regions of higher pitch. Every one who is familiar with such transmission systems knows well that these high-frequency components are nearly always eliminated. While

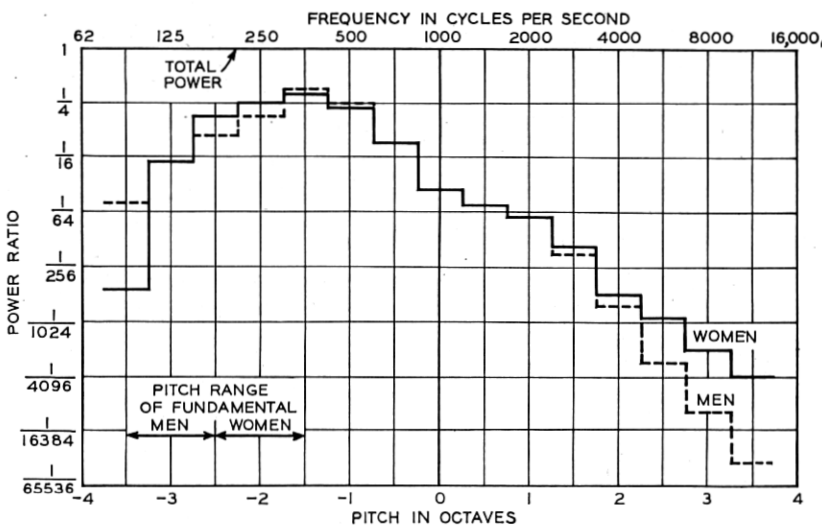

Fig. 4—Distribution of speech power in fractions of the total power for half-octave intervals above and below 1000 cycles.

these sounds are not of controlling importance in properly understanding speech, it is evident that the women's voices are somewhat handicapped as compared with men in systems which eliminate them.

Hearing

Paralleling our research on speech sounds, an investigation of hearing has been under way in Bell Telephone Laboratories. Broadly speaking, the aim has been to arrive at an accurate physical description and a measure of the mechanical operation of human ears in such terms that we may relate them directly to our electrical and acoustical instruments. We have measured the keenness of the sound-discriminating sense, and determined what is the smallest distortion which the mind can perceive, and how it reacts to somewhat larger distortions. This information is utilized in determining a reasonable basis of design both for separate instruments and for transmission systems as a whole, to give a proper balance between cost and performance.

I can only indicate a few of the important results of our investigations. One of the first steps was to determine in a quantitative way the performance of our ears as machines. It was obviously important to know how faint a sound the ear can hear, and also how loud a

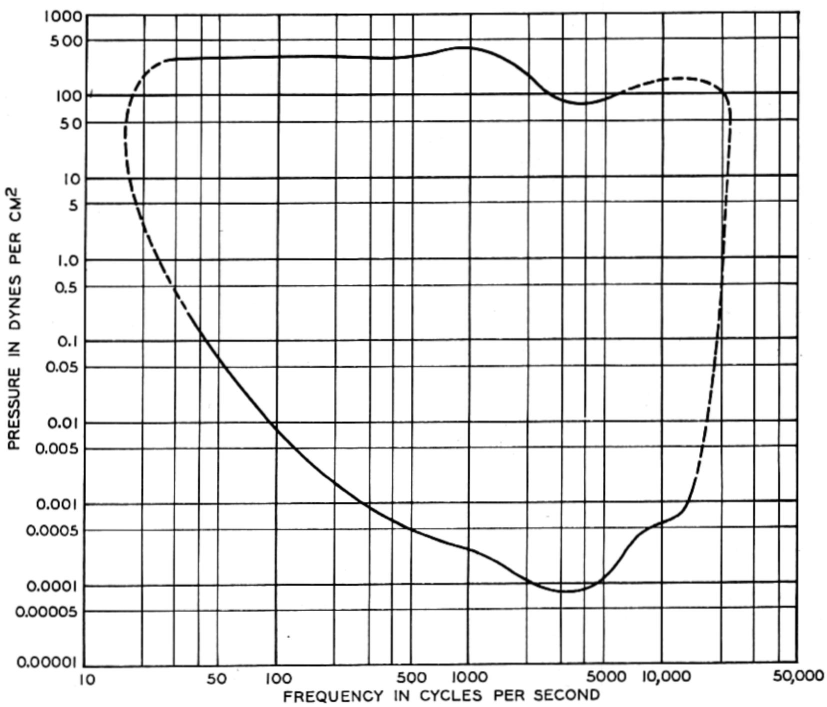

Fig. 5—Auditory sensation area for the typical ear of a young adult.

sound the ear can tolerate. With the advent of the vacuum tube, it was possible to develop methods of accurately measuring the intensity of faint sounds and of readily producing such sounds. Figure 5 gives the results of a large number of measurements made to determine the limits of hearing. This graph is called the auditory sensation area. The lower solid curve represents the minimum sound that an average young person can hear. The abscissa gives the frequency of the pure tone, and the ordinate the sound pressure in dynes per square centimeter. The top solid curve represents the maximum intensity of sound that the ear is capable of handling. This curve was determined by noting that intensity which produced a feeling sensation. Intensities slightly higher than this result in pain and in some instances serious injury to the ear. The dotted lines on either side complete the enclosure and represent the upper and lower limits of pitch that can be heard. It is obvious from this figure that the upper or lower limit of pitch is greatly dependent upon the intensity at which the sound is produced. It will be seen that near the middle range of frequencies, the pressure range is one million to one. The pitch range of pure tones is from about 16 to 25,000 cycles per second.

These results are for young adults, and it may be of interest to note that as one becomes older the hearing acuity, at the higher frequencies particularly, becomes less. In the table below is shown some measurements to determine what the effect of age would be upon the hearing acuity:

TABLE III

DB LOSS IN HEARING WITH AGE

Frequency	60 to 1024 Cycles	2048 Cycles	4096 Cycles	8192 Cycles
Ages 20–29 (96 ears)	0	0	6	6
Ages 30–39 (162 ears)	0	0	16	11
Ages 40–49 (84 ears)	0	2	18	16
Ages 50–59 (28 ears)	0	5	30	32

These are average values obtained from measurements on a large number of persons.

Another important measurement of average hearing is that concerned with minimum perceptible differences in pitch and in intensity. Careful measurements on large groups of people have given us reliable data of this form. In Fig. 6 are shown the results of such measurements. They are plotted on the auditory sensation area. The ordinates are decibels above the reference pressure and the abscissas are centi-octaves above or below a pitch of 16.35 cycles per second. A frequency scale is also given for reference purposes. The numbers within the area indicate the minimum changes in the intensity level in db that the average ear is able to detect over that region of the auditory area. It will be seen that near the threshold fairly large changes are necessary to be perceptible, while at fairly high intensities about 1/4 decibel is all that is necessary for the change to be perceived.

In Fig. 7 are given similar data for minimum perceptible differences in pitch. The numbers in the figure in this case are given in centi-octaves; that is, each unit corresponds to 1/100 of an octave. The results of this line of investigation have an important bearing on the physiological theory of hearing which I cannot enter into, and another important result has been the development of methods of determining the degree of impairment of hearing.

In telephony we are, of course, not directly concerned with simple sounds, but with the highly complex sounds of speech, and these are

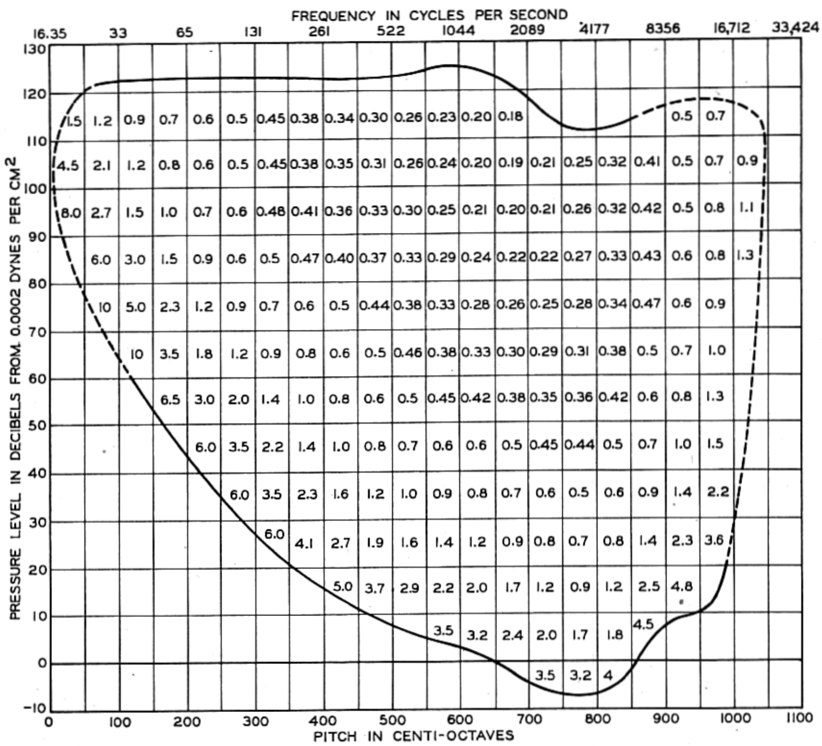

Fig. 6—Minimum changes in intensity level in db that the ear is able to appreciate at various positions in the auditory area.

on actual telephone circuits generally associated with extraneous sounds which we may group under the broad term of noise. Further, telephone instruments are not perfect, and could be made to approach perfection only at a great expense. In order to arrive at a quantitative understanding of the importance of departures from perfection in telephone transmission elements and conditions of use, we have in very general terms proceeded as follows: We set up transmission systems so nearly perfect that even the keenest ear could not find a flaw in their transmission performance, and then introduce measured imperfections or variations.

By this general process, we were able to determine the effect of noise of chosen intensities either as noise present in the telephone receiver or as noise in the room. Similarly, the effect of a line or other characteristic such that voice frequencies above a certain value or below a certain value were not transmitted, was determined. The

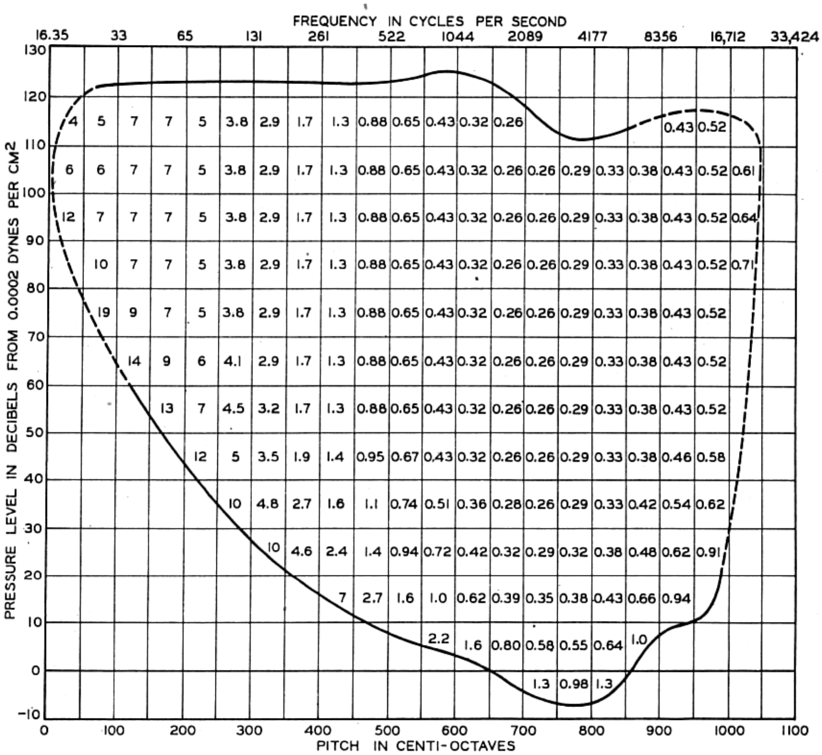

Fig. 7—Minimum perceptible differences in pitch in centi-octaves for various positions of the auditory area.

effect of introducing a highly resonant element or of a non-linear element was studied. The range in loudness of speech necessary for best reception was likewise measured.

As noise became recognized as a very real factor, a standard basis for noise measurements was established. Consequently we are now able to measure noise on a telephone circuit or in a room, and state the result in terms of a standard unit.

Materials

In the practical design of modern telephone instruments we owe a large debt to the chemist and the metallurgist. Modern molding materials and processes are utilized in order to secure forms of apparatus satisfactory from the standpoint of appearance and of mechanical strength. The newer types of permanent magnet steel, to the development of which your countrymen have contributed so largely, provide possibilities of light-weight and very efficient magnetic structures.

It is a most striking circumstance that commercial telephony is dependent upon the performance of a small mass of carbon granules in the transmitter. No single material entering into the construction of telephone apparatus has therefore greater importance. In America at least, transmitter carbons are largely derived from a certain specially selected anthracite coal. In its natural state, this coal exhibits none of the characteristics required for its use in a transmitter. These characteristics or properties are secured by heat treatment. These heat-treatment processes were for many years the result of empirical development and were not well understood or, as we now recognize, adequately controlled. This resulted in a product of uncertain quality. An important task of the Laboratories was therefore to study each step in the process of producing carbon and to develop a process definitely specified at each step, which would be capable of giving the desired uniform quality. The results so far obtained have had very important reactions upon transmitter performance. The Laboratories have also set themselves the more elementary task of understanding the fundamental properties of carbon contacts. One important element of this research is to determine the causes of resistance changes produced when the compressive force on a mass of carbon granules is changed. It is too early to report results from this research, but it seems clear that granular carbon will be an important element in the design of transmitters for many years to come, and we should seek to obtain complete fundamental knowledge of its operation.

Testing Methods

Broadly speaking, methods of testing have been developed, first, to enable the development and design engineer to determine quantitatively the various performance factors of the apparatus under development, and second, to determine how well the apparatus which has been developed performs under service conditions. In the Laboratories, we have over the last twenty years developed methods for measuring the physical constants of the apparatus involved so that we can analyze this apparatus as electromechanical structures. Further, in the design of telephone transmission apparatus we are concerned with a power transmission system in which the design engineer has no control over the power source, the human voice, nor over the receiving agency, the human ear. His control is limited to the conveyance of power from speaker to listener. In the Laboratories, therefore, we have recognized that it is necessary, at least without present knowledge, to supplement physical measurements by measurements involving speech sounds and the human ear. Some years ago, these tests consisted of comparisons between different instruments or transmission elements made by the process of talking first over a circuit containing, for example, one instrument, and then over the same circuit containing a different instrument. Dependence was placed wholly upon the listener's skill to detect differences in volume, quality and intelligibility. It was recognized that this method of testing left much to be desired. Owing to the limitations of the human ear, small volume differences could not be detected, but even more important, this simple test furnished no very accurate measure of speech distortion affecting intelligibility, and obviously no definite information as to the relation between volume, various types of distortion, and overall effectiveness.

Dr. George A. Campbell, in 1910, proposed a method of testing which has been highly developed in our Laboratories. This method, termed "articulation testing," measures the relation between the reproduced and impressed sounds from the standpoint of effects on intelligibility of different kinds of distortion. This method has been described in a number of publications. Briefly, in this method, lists of syllables chosen at random and usually meaningless monosyllables are called over the circuits to be rated, and the percentage of syllables correctly understood gives a measure of the circuit performance. Further, the method has been extended to give quantitative measures in terms of the recognizability of reproduced speech sounds, of the effects of loudness of these sounds, and of the noise which may be present.

While various physical tests and the articulation test method are exceedingly useful tools in the hands of the research and development engineer, they do not give a direct measure of the transmission service performance of a circuit in terms of the ability of the user to carry on a conversation under actual commercial conditions. This ability of the user to carry on what may be termed a successful telephone conversation depends not only upon the performance of the telephone instruments and circuits but also, to a substantial extent, upon the users' own performances—the subject material of conversation, how they talk into the transmitters, and how they hold the receivers—and upon the room noise conditions. In other words, there are a number of factors random in nature which, while beyond the control of those who design and engineer the telephone plant, must be taken account of in rating the service performance.

A large amount of thought and effort has been given to the problem of how best to determine transmission service performance. Very briefly stated, we have been led to the following steps: In order to take suitably weighted account of all the factors involved, service performance ratings should be based on service results, that is, transmission service performance should be measured by the success which users of the telephone circuit have in carrying on conversations over the circuit. With the various factors in mind, we have fixed upon what we have termed "effective transmission" ratings for transmission plant design. These ratings are based on a determination of the *repetition rate* in normal telephone conversations.

As the effect of a change in a circuit depends upon its initial characteristics, it is necessary in order to be able to compare numerical results to have a basic circuit for reference. By suitable choice of basic circuit, it is possible to express the effects of changes in any one transmission characteristic in terms of the attenuation of the trunk. For example, the effect of changes in sidetone level in the subscriber's set can be expressed as so many decibels change in trunk attenuation. Mr. W. H. Martin's paper, "Rating the Transmission Performance of Telephone Circuits," in the *Bell System Technical Journal*, January, 1931, discusses the method and general principles. It should be noted that the application of the method requires careful consideration of many factors and the accumulation and analysis of a very substantial amount of data. Based on these data, we have arrived at the following relationship:

$$\text{Relative effective loss in db} = 50 \log_{10} (r)$$

where r is the ratio of the repetition rates for the two conditions compared.

Association of Transmitter and Receiver

In order to furnish a convenient two-way talking circuit over a single pair of wires, the transmitter and the receiver at each end of the circuit must be continuously associated in the circuit. This has been accomplished by various circuit arrangements since the early days of the telephone, and as every user of the telephone knows, leads to the condition that when speaking into the transmitter one hears his own voice in the receiver. Local speech so heard is designated as sidetone. The Laboratories have carried on research in order to determine the effect of sidetone on the overall efficiency of the circuit. We find that sidetone above a certain volume decreases the conversational efficiency of the circuit. Parallel with the study of the effects of sidetone, research has been carried on on methods which could be applied to limit sidetone in amount to more nearly its optimum value. This has led to the development of what are known as anti-sidetone circuits, which do not eliminate sidetone but reduce it to an amount which is more nearly that found to be desirable.

An important step in the association of the transmitter and the receiver is represented by the handset which provides a rigid mechanical connection between the two units. This rigid mechanical connection introduces mechanical coupling between the receiver and the transmitter, which had to be given very serious consideration in order to avoid speech distortion.

Trends in Instrument Development

I have broadly indicated to you fields of research which underlie the development and design of the telephone transmitter and receiver. It will now be of interest for us to note what application is likely to be made of the results of what has amounted to an enormous total of scientific effort. In this connection, it may be well again to emphasize that station apparatus is intimately associated with the user, and has therefore to be designed to fit him, his habits of using the telephone, and the conditions attending such use. The handset has to be designed to fit his head, the holes in the dial to fit the size of his finger, the bell to be loud enough, and so on. Our effective transmission rating system has been set up in an attempt to rate the performance of the telephone when employed by the customer in the way he wants to use it, under the conditions surrounding him. For this reason, this method of rating has been found particularly valuable in the development work on instruments.

Because of the wide range of customer usage and conditions, a number of factors have to be taken into account in the design of the apparatus. Also, because this apparatus is located on the customer's premises, where it is relatively inaccessible to the telephone personnel, it must be capable of standing up without undue trouble under this wide range of usage and conditions. To strike a proper balance in meeting all these factors requires an intimate knowledge of the field conditions as well as of the development and manufacturing possibilities. A continuing close contact with field experience is employed to modify the designs towards securing the proper balance to meet these factors.

In order to indicate more clearly the present trends in design, I shall refer briefly to the earlier art. In the early development of transmitters and receivers, the matter of getting efficiency was of primary importance since this could be evaluated directly in terms of the amount of copper required in the connecting line. The early transmitters, which were of the same construction as the receiver, depended on the generator action of a diaphragm and coil and developed sufficient power to be heard over only a few miles of heavy-gauge wire. Some amplification was necessary before telephone communication could begin to assume the proportions of a widespread service. This amplification was obtained at a reasonable cost in the carbon contact transmitter. Transmitters of this type are in the order of 60 db more efficient as transducers of acoustic to electric energy than the earlier type.

Both the transmitter and the receiver operate by means of diaphragms which have natural periods of vibration. These resonances and the resonances of the air spaces on each side of the diaphragm were used to obtain as efficient a transfer of energy as possible. In the early design, a great deal of attention was also given to locating these resonances at the portion of the frequency range where they would tend to increase the intelligibility of the reproduced sound. As a result, both instruments were made very efficient in the region of 1000 cycles, which lies within the range where the ear and the sensation of loudness are most sensitive.

It was recognized that these resonances caused undesirable distortion, but under the conditions the resulting increase in efficiency more than compensated for this disadvantage. As time went on, the diaphragm resonances came to be looked upon as practically inherent in commercial transmitters and receivers, because no way was known of eliminating them without making a very material sacrifice in the efficiency of the instrument.

About twenty years ago, the development of the vacuum tube amplifier and the high quality condenser transmitter made it possible to demonstrate and measure quantitatively the advantages of reducing distortion. These high-quality instruments, the improvement in measuring technique and the development of improved methods of designing vibratory systems offered the promise of providing instruments in which the resonance effect could be reduced without unduly affecting efficiency.

The first commercial instrument for station use, which demonstrated the possibility of carrying out this promise, was the transmitter employed in the handset first supplied by the Bell System in 1927. This transmitter had to meet the requirement of giving the same transmission service as transmitters of the deskstand type, and at the same time meet the very exacting requirements imposed by the handset to make it free from howling and capable of performing over a wide range of positions. The diaphragm resonance was damped to a large extent by the use of paper rings and, by lightening the structure, the point of maximum response was moved up in frequency so that it no longer coincided with the peak of the receiver. The effect of this was not only to broaden the response characteristic and improve intelligibility, but also to reduce the gain in the local howling circuit which is, of course, a maximum when both transmitter and receiver have their greatest efficiency at the same frequency. The same separation of peaks resulted in the received speech being less loud, but in spite of this the overall performance was equivalent to that of the best deskstand type of instrument then available.

With this accomplishment, further work was directed toward maintaining the lower distortion and increasing the efficiency. The transmitter introduced in 1934 represented a marked improvement along this line. This instrument still further broadens the transmitted frequency range and is used with about the same efficiency in deskstands, handsets, wall sets, and coin-collect sets.

A new type of handset will be introduced in the Bell System in 1937 which, in addition to having a more pleasing and simplified design, will incorporate the new transmitter mounted in such a way as to make fullest use of its ability to transmit efficiently over a wide-frequency band.

During this evolution of the transmitter, the knowledge which had been gained as to the importance of transmitting different widths of frequency band over commercial telephone circuits led to the establishment of the range from 250 to 2750 cycles for designs of new circuits. It was not the intention in the establishment of this range that circuits should not do better than this where it is possible without materially increasing cost, but that all circuits should be at least as good as this. The establishment of this frequency range took into account a number of factors of which a very important one is that the overall utilization of this range from the sound entering the transmitter to the sound output of the receiver provides a grade of transmission which is highly satisfactory for the reproduction of conversational material.

The establishment of this frequency range played a part not only in the design of circuits, but also in guiding the evolution of the transmitter and receiver. The transmitter last referred to meets this requirement very well. In fact, its efficiency is fairly uniform for a frequency range extending beyond 4000 cycles.

The next step in the process was to improve the performance of the receiver. A pronounced resonance at 1000 cycles was no longer necessary since means had been found to improve the efficiency of instruments in other ways than by concentrating all the resonances at one frequency. The importance of the higher frequencies in transmitting and reproducing the transient sounds characteristic of the consonants in speech led to placing more emphasis on these frequencies and attempting to produce more uniformly the band of frequencies which was set as a limit for circuits. This has now been accomplished in a practical fashion in the receiver which is being introduced in 1937.

The effect of this evolution in the design of station instruments may be brought out by a comparison of the overall response characteristic —that is, the relation of the sound delivered to the ear to the sound available at the transmitter—for a typical telephone connection having, in one case, both terminal instruments of the 1920 type and, in the other case, the terminal instruments of the coming new 1937 type. In this typical circuit, the trunk has been taken as free from distortion so that its effect will not influence the indicated performance of the instruments, although the circuit does include two 22-gauge loops each three miles long.

At the resonance point of the old instruments, just over 1000 cycles, the overall response in going to the new instruments is reduced by almost 30 db while the response in the range from 2000 to 3000 cycles is increased by over 20 db. In the frequency range from 500 to 2000 cycles, the circuit employing the older instruments shows a variation of overall response of over 30 db. For the new type, the variation for this same frequency range is reduced to 15 db, and, furthermore, this variation of 15 db applies approximately for the range of 250 to 2750 cycles which was mentioned as the transmission range requirement for the design of new circuits. In regard to the variation of 15 db in this frequency range, there is good indication that this response is more desirable than one of no variation, from the standpoint of having the telephone performance approach that of direct air transmission.

In addition to these improvements in frequency response and efficiency, the intensive development program on these instruments has improved materially the stability of the carbon transmitter under service conditions. This is an important factor in extending the useful life of these instruments and in reducing the cost of maintaining the desired transmission performance.

You will perhaps pardon me if, in concluding, I say a few words which I hope will not seem unduly laudatory of the work of my associates in the Bell Laboratories. The facts seem to be that twenty years ago or thereabouts, there was very little general scientific interest in sound and sound devices. As a result of work begun in

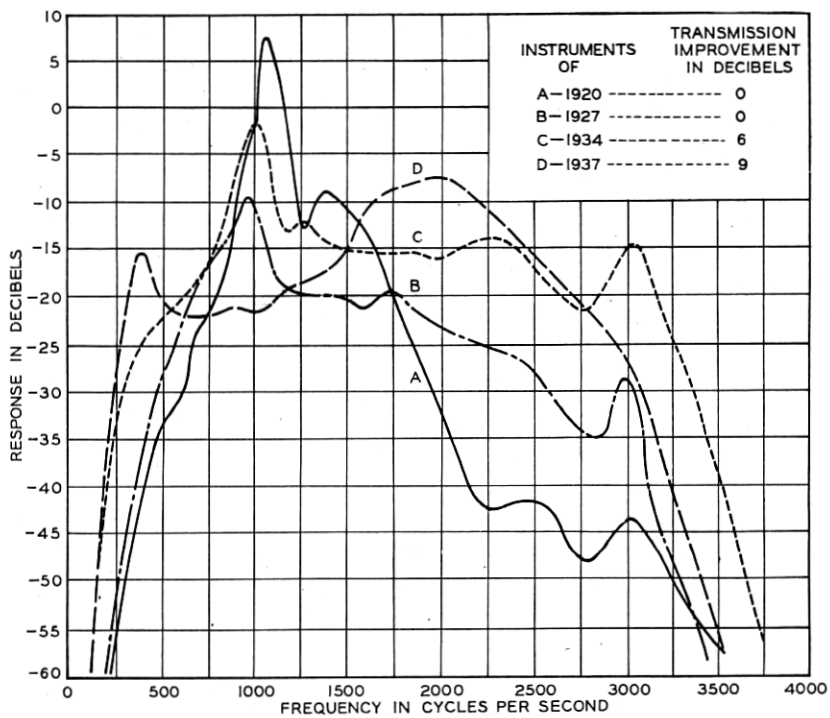

Fig. 8—Comparison of the response-frequency characteristics of telephone instruments since 1927.

these Laboratories, and as the possibilities of interesting and important applications became apparent, broad scientific interest was stimulated, and we have seen and welcomed increasing research activity in sound and acoustics in many of the university laboratories and in new industries based upon the results of scientific research in sound initiated by us. A number of my associates have attained world-wide recognition for their scientific and technical accomplishments. Our scientific investigations were undertaken to enable us to develop further the telephone art, and the results of these investigations are serving to guide us not only in the development of telephone instruments but in all developments of telephone transmission. The Laboratories' scientific and design work has contributed in large measure to the improvement of methods of recording and reproducing sound in the phonograph and sound-picture arts. The art of radio broadcasting owes a large debt to the work of the Laboratories, not only for the fundamental scientific knowledge contributed but also for actual instrumentalities employed. To those with impaired hearing, the Laboratories' investigations have made possible improved means for determining the extent of their impairment, and improved hearing aids. Finally, at least in America, we are becoming what I may term as "noise conscious." In our cities, noise is being recognized as a factor affecting comfort, efficiency, and possibly even health. The development of accurate methods for the measurement of noise is contributing to studies looking towards the reduction of noise.

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