THE SENSITIVITY OF THE EAR AS A FUNCTION OF PITCH

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Abstract

Sensitivity-frequency curves as determined by continuously varying the pitch for different intensity levels.—The threshold sensitivity curve for audition may be determined by varying the intensity at many different pitches, or by varying the pitch at many intensities, noting the ranges of pitch which are audible for each intensity. The latter method enables irregularities in the curve to be more easily and surely determined. In these experiments, a thermophone actuated by current from a vacuum tube oscillator was used, the pitch being controlled by means of a continuously varying inductance, and the threshold sensitivity curve for the frequency range of 360 to 3000 per sec. was determined by the use of successive levels of intensity having an intensity ratio of 2:1. Curves were obtained for *thirty normal ears. They show remarkable individual irregularities*, not only being different for different individuals, but often for the two ears of the same person. In several cases the sensitivity changes by a factor of 200 to 1000 with a change of pitch of a semi-tone. An acceptable theory of the mechanism of audition must explain such abrupt changes. The *average sensitivity* increases from $10^{-7.2}$ for 360 to an approximately constant value of $10^{-8.6}$ ergs/cm^2/sec. for frequencies above 1300 per sec.

MANY investigations have been made of the sensitivity of the human ear and of the difference in sensitivity for different pitches.[1] The subject is of importance from the standpoint of the sensitivity of the ear as a piece of physical apparatus and because of the bearing of the results on theories of the mechanism of hearing, besides the medical diagnostic value of tests for deficiency in hearing. The sensitivity of the ear can best be expressed in terms of the minimum sound intensity which is audible. The number scale here used for expressing sensitivity is the logarithm to the base 10 of the reciprocal of the minimum intensity necessary for audition; thus sensitivity $= \log_{10} 1/J$, where J is the intensity expressed in ergs per square centimeter per second.

The greater portion of the apparatus used in the present work was similar to that described in a recent paper by the author in this journal.[1] A thermophone was used as a source of sound, this consisting of a thin

[1] The most extended of these investigations are: Zwaardemaker and Quix, Arch. Anat. Physiol.; Physiol. Abt., Supp., p. 367, 1902; Wien, Arch. f. ges. Physiol. **97**, 1, 1903; Dean and Bunch, Laryngoscope, August, 1919; Minton, Phys. Rev. **19**, 80, 1922; Lane, Phys. Rev. **19**, 492, 1922; Fletcher and Wegel, Phys. Rev. **19**, 553, 1922; Kranz, Phys. Rev. **21**, 530, May 1923.

strip of platinum mounted in a small telephone receiver case held tightly to the ear of the observer. The sound is produced by expansion of the air caused by the periodic heating of the platinum strip by an alternating electrical current flowing through it, this current being supplied by a vacuum tube oscillator. The circuit arrangements are shown in Fig. 1. The pressure changes produced in the ear cavity were obtained by the use of the formula given by Wente[2] which involves the frequency and amplitude of the currents used and the constants of the thermophone. The corresponding sound intensities were calculated from the values of the pressure changes.

In determining the limit of audibility as a function of frequency, it is conceivable that either one of two procedures may be used. The fre-

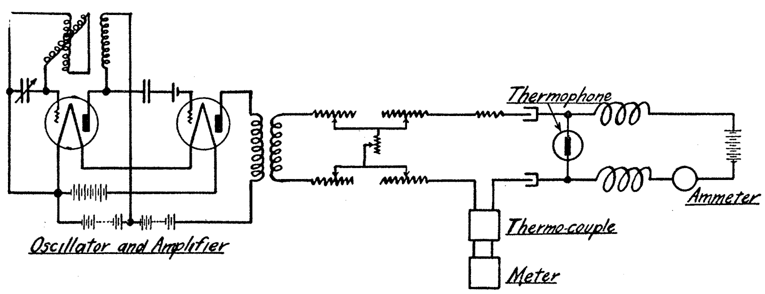

Fig. 1. Diagram of apparatus.

quency may be kept constant and the intensity varied continuously or in small steps until the limit of audibility is reached, and by taking different frequencies successively, the required curve may be obtained point by point. This indeed has been the procedure used in all of the work on ear sensitivity in which the actual ratios of the energies at different frequencies have been obtained. It is clear however, that there must always remain an uncertainty as to what is the nature of the curve between the discrete frequencies used.

The other possible method is to vary the frequency back and forth over a considerable range, the intensity being changed by successive increments. Thus for different intensities near the low limit, different portions of the frequency range will in general be audible. By a suitable choice of the intensity increments, the desired curve of relationship between frequency and necessary intensity for audibility may be determined as accurately as is desired, and the amount of assumption involved in the completed curve will be known. Any peaks of dips in the curve which

[2] Wente, Phys. Rev. **19**, 336, 1922

extend over a narrow range of frequencies will be easily detected by this method, while with the use of discrete frequencies it would require a prohibitive amount of time and work to take a sufficient number of points to locate and measure all the possible peaks and dips in any extended range of frequencies. Seashore, Dean and Bunch[1] have worked on this second method, obtaining a continuous change of frequency over a considerable range by the change in speed of rotation of an electrical generator, the resulting current being put through a telephone receiver. Various shunts were put across the telephone receiver to give various levels of intensity. By this method deficiencies in audition over a portion of the range can in general be detected. No attempt was made to get absolute values of intensity, and indeed actual ratios of intensities at different frequencies were not known because of the unknown characteristics of the telephone receiver and of the generator.

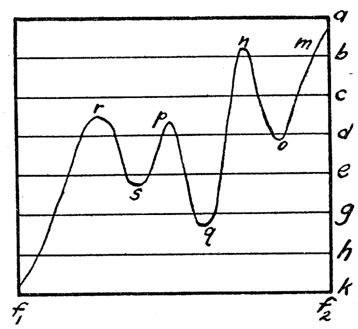

Fig. 2. Diagrammatic curve.

In the present experiment, the second of the two methods was used, the frequency change being effected by a change in the inductance in the oscillating circuit of the vacuum tube oscillator. The inductance coil was made in sections which could be separated, these being mounted on a sliding device equipped with a pointer traveling over a scale for calibration purposes. It was found possible to vary the frequency satisfactorily over a range of a little less than an octave by thus changing the inductance, and different ranges of frequency were obtained by varying the capacity of the oscillator circuit. Several slightly overlapping ranges were used, which together covered the frequencies from 360 to 3000 per sec. It may be remarked that frequencies above this latter figure are of small practical importance as far as speech is concerned.

The principle of the present method is illustrated in Fig. 2. Suppose the form of the sensitivity-frequency curve is as shown, between the frequencies f_1 and f_2. The higher sensitivity of course corresponds to the less intensity. Let the levels of intensity used be as shown by the horizontal lines *a* to *k*. At the intensity level *a*, nothing is audible as the frequency is varied from f_1 to f_2. At the level *b*, parts of the frequency range corresponding to portions *m* and *n* of the curve are audible. At the level *d*, peaks *p* and *r* are noticeable and the gap at *o* is narrowed. At level *e*, the dip *o* has disappeared and all of the frequency range is heard from f_2 to a point on the *nq* slope. At level *g*, the gap *s* is no longer found and at level *h*, all of the frequency range from f_2 nearly to f_1 is audible. So it amounts to taking horizontal sections of the sensitivity-frequency curve and these sections can be as numerous as the experimentor wishes and so the curve may be determined with as great a degree of accuracy as is desired.

The procedure of the test was to have the subject control the frequency by means of a handle on the inductance coils. The current was first reduced by the operator until the sound was insufficient to be audible to the subject at any point in the range being used. The current was then increased in steps with a ratio of approximately 1.4 : 1, the corresponding intensity changes having ratios of 2 : 1; that is the intensity was doubled at each change. After each current change, the subject varied the inductance and determined what portion of the range he could hear, the alternating current values at the limiting frequencies and sometimes at intermediate frequencies being read by the operator on the thermal ammeter which was always in circuit. The frequencies were then read from a preliminary calibration of the inductance scale. The current was increased by steps until all of the range was heard.

Results

Figs. 3 and 4 show the sensitivities of the ears of some of the individuals tested by this method. The observations on the left and right ears of the individual are marked as L and R respectively. All of the people examined would be rated as normal hearing people in the popular sense of the term and had never experienced any difficulty in hearing.

The absolute values of sensitivity are found to vary between 10 and 6 in the range of frequencies used. This means that intensities of from 10^{-10} to 10^{-6} ergs/cm^2/sec. are audible. Of the small variations shown in all of the curves, many are undoubtedly real although the accuracy of the measurements is not in general much better than 0.3 in logarithmic sensitivity due to the magnitude of the intensity increments used in these tests. In any case the small variations probably do not have much significance. It is seen that there are no pronounced peaks or depressions of sensitivity common to all ears although a decrease at the lower end is quite well established, in agreement with previous work of the author and others.

Fig. 3A is of a type which shows no irregularities of any consequence in the frequency range covered. Fig. 3B represents the sensitivity of an individual having no mastoid cavity on the right side. The effect on the hearing is certainly not great, for although below 1000 per sec. the right ear is somewhat less sensitive than the left, the difference is not sufficient

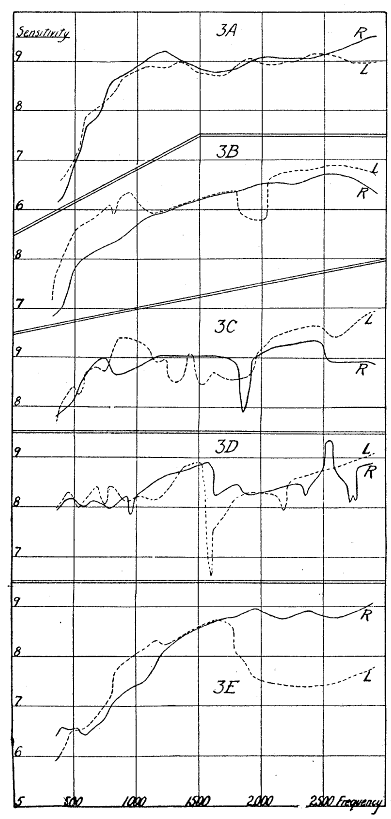

Fig. 3. Sensitivity curves for individual normal ears.

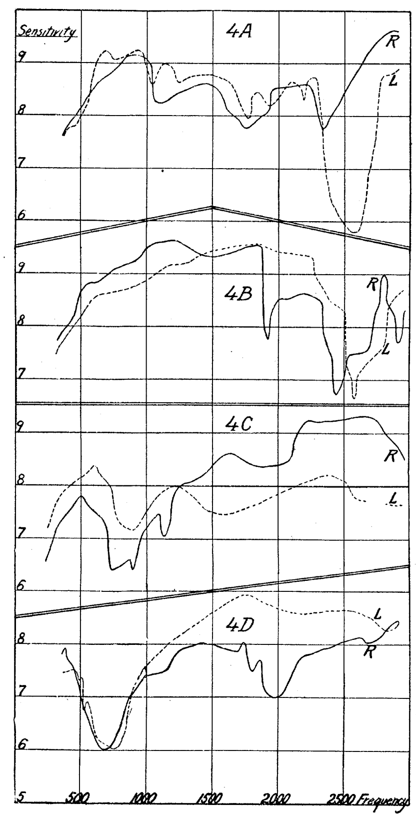

Fig. 4. Sensitivity curves for individual normal ears.

to be of any practical importance. The left ear shows a depression of small consequence in the neighborhood of 2000. Fig. 3D shows a similar depression at a frequency of 1600 which is very narrow in the lower part. On the low frequency side of this depression, the change in sensitivity is quite abrupt, with a sensitivity change of 2.3 or a change in intensity by a factor of 200 in passing over a frequency change of 80 cycles, which is here a little less than semi-tone. This dip is a good illustration of the type of sensitivity variation which would probably not be located at all by the method of tests with discrete frequencies, and if located it would be very difficult to determine its limits or indeed to locate the lowest point of the sensitivity. The other figures show depressions over part of the frequency range, the width and depth of the depressions varying considerably. Rather broad depressions, coming back up to the average height on both sides, are shown by several of the curves, one of the most pronounced of this character being in Fig. 4A. The depth of this depression corresponds to a change in logarithmic sensitivity of 3, or an intensity ratio of 1000. Fig. 3E shows a diminished sensitivity for all frequencies above 1800. Fig. 4B shows rather narrow holes within fairly wide areas

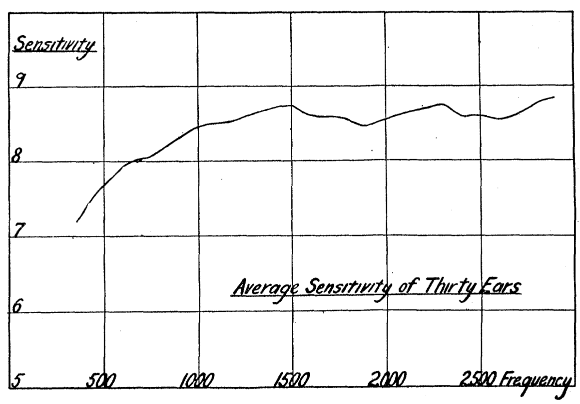

Fig. 5. Average sensitivity of thirty ears.

of depression. Figs. 4C and 4D show deficiencies in sensitivity for the lower part of the frequency range, the depressions in Fig. 4D being especially marked and extending from 400 to at least 1000, an interval of more than an octave, and involving both ears. Fig. 5 shows the average curve of sensitivity for the thirty ears which were tested, attained by averaging the sensitivities as above defined.

It may be noted that in some cases of considerable deficiency in sensirivity for one ear of an individual, there is a tendency toward deficiency for the other ear in the same range. This is not true for all of the individuals however.

Discussion

The abruptness of the change in sensitivity in passing over the frequency range is in many cases very marked and is probably the most striking feature of the results here presented. An explanation of the abruptness of these changes in sensitivity must be included in any comprehensive theory of the mechanism of audition. Pictorially it would seem to require the physical existence of a large number of elements (1) which are each concerned with the transmission of only a very narrow range of frequencies, (2)which exist either in the inner ear or in a possible nerve cable from the ear to the brain or conceivably in the brain itself or in all three places, and (3) which are of such a nature that individual e'ements may be quite severely injured without seriously affecting neighboring elements. If, as many theories of audition suggest, a differentiation between frequencies is made in the inner ear, it is hardly reasonable to suppose that the impulses are again compounded to be sent to the brain over a single nerve, and so a bundle or cable of nerves would be needed for the connection between ear and brain. It is conceivable that the nature of the different strands of this cable are such as to accentuate the differentiation between frequencies originally made, perhaps not so very sharply, in the inner ear. At any rate, injury to individual strands of this cable or to the terminal apparatus on either end would, if the frequency discrimination were sufficient, serve to explain the abruptness of the changes in sensitivity which are found.

As for the method here used, one advantage is that absolute values of sensitivity are found, but perhaps the unique advantage is that no assumptions are made as to the continuity of the sensitivity over any part of the frequency range covered, this distinguishing it from all methods using tests at discrete frequencies. With the latter type of test, the resulting curve may take a wide variety of forms depending on the particular frequencies chosen for the tests. The use of a continuous frequency range makes possible the easy and accurate testing of the sharp breaks in sensitivity mentioned above, which would be very difficult by any other method. The method thus seems to make possible more thorough and accurate analyses of audition than any heretofore used. The thermo-phone serves well in testing normal or nearly normal ears, while a properly calibrated instrument of greater efficiency such as an electromagnetic type with the natural frequency of the diaphragm above the range to be used, would be better suited to the testing of more deficient ears.

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