A New Determination of the Equal-Loudness Contours*

D. W. ROBINSON†

Summary—**The results of a redetermination of the equal-loudness contours for pure tones, carried out at the National Physical Laboratory, Teddington, England, are discussed in relation to earlier data. The new measurements cover a wider area of the auditory diagram and were obtained by a comparatively large number of listeners. This has enabled the results to be classified into sex and age groups. The latter factor is shown to dominate high-frequency hearing. Some data are presented on the reliability of laboratory measurements of loudness and on certain features of a well-known discrepancy between the thresholds of hearing under free-field and earphone listening conditions.**

Introduction

ACOUSTICS is commonly defined as the science of sound, and if we seek further for a definition of sound we shall get, at least in the English language, the ambiguous answer that it is both a mechanical disturbance propagated in a medium and the sensation of hearing produced by the disturbance. This duality is reflected in the work of the acoustical engineer. Largely by manipulations of a purely physical character, he aims to achieve a desired sensation within the hearing processes of a listener. To bring about a satisfactory junction between the dual aspects of sound, the engineer must have, as an essential part of his equipment, a proper knowledge of the relations between the physical and psychological aspects of sound—the so-called psychoacoustical data.

It is possible to visualize a multidimensional relation between the various physical magnitudes (sound pressure, frequency, direction of wave propagation, duration, spectral distribution, harmonic distortion, and so on) on the one hand, and a set of psychological correlates (loudness, pitch, brilliance, annoyance, "presence," and so on) on the other. In one or two cases there is a fairly direct correspondence between members of each set, whereas others involve many factors. Early in the development of modern acoustics, it was appreciated that the relations between frequency and intensity of pure tones and their loudness have a leading place in this connection.

There are various reasons why loudness has received more attention than other factors in spite of the obvious fact that other attributes of a sound can be of importance. It is perhaps true to say that this emphasis stems from the experimental fact that loudness is amenable to fairly precise measurement. In the case of pure tones, the loudness depends primarily on the frequency and intensity of the tone. Other factors such as the wave direction, duration, previous history of sound exposure, and the mode of listening have some effect. These, however, can be experimentally controlled and handled as "corrections" to a set of primary data.

As with any psychological magnitude, the loudness necessarily is personal to each listener and can be determined only by subjective experiments. Differences between the judgments of different listeners can be attributed partly to physical causes (such as variations in bodily dimensions), partly to physiological differences giving rise to different patterns of neural activity for the same sound stimulus, but in the last resort to differences in the perceived sensation. With some "perceptual continua" such as annoyance, there seems to be no limit to variability in the third of these categories. In the case of loudness it has been shown convincingly over a number of years that the judgments of different listeners fall within limits narrow enough to justify the concept of a statistical "normal listener," at least for practical purposes. Some experimental data on the reliability of loudness measurements are presented in this paper.

In addition to their scientific interest in connection with the mechanism of hearing, the equal-loudness relations are concerned in a variety of practical applications. A familiar example is the reproduction of music using frequency weighting networks selected according to the level. Aside from entertainment there are important applications to the measurement of sound level, to various methods of calculating the loudness of complex sounds from objective measurements of their spectra, to certain methods of diagnosis of hearing impairment, and so on.

The well-known curves of Fletcher and Munson[1] have been in use for these purposes for a number of years, but their results had been challenged as long ago as 1937 by Churcher and King[2] who carried out their experiments in a rather more direct manner. Differences were apparent in all parts of the auditory diagram, and amounted in places to 30 phons or more, errors which are greatly in excess of the internal consistency of the respective determinations. It was impracticable to resolve these discrepancies on paper, and as a result of repre-

* Manuscript received by the PGA, January 30, 1958. The work described was carried out as part of the research program of the National Physical Lab., and this paper is published by permission of the Director of the Laboratory.

† National Physical Lab., Teddington, Middlesex, England.

[1] H. Fletcher and W. A. Munson, "Loudness, its definition, measurement and calculation," *J. Acoust. Soc. Amer.*, vol. 5, pp. 82–108; October, 1933.

[2] B. G. Churcher and A. J. King, "The performance of noise meters in terms of the primary standard," *J. IEE*, vol. 81, pp. 57–90; July, 1937.

sentations by the committee of the British Standards Institution charged with preparing national standards for noise measurement, the National Physical Laboratory undertook to redetermine the relations taking advantage of improvements in technique since the 1930's. The opportunity also would be taken to extend the intensity and frequency range of the earlier work. By employing a comparatively large group of listeners, it was intended to provide a basis for possible standardization of a set of loudness relations acceptable to all workers in the field. These objectives are now within sight largely through the encouraging progress made at a meeting of the International Organization for Standardization (ISO) in 1957 at which provisional acceptance of the new results was secured.

This paper is concerned principally with the results of the new determination of the pure-tone equal-loudness contours of which a full description has been published elsewhere by Dadson and the author,[3] and it is relevant to discuss the results in relation to other work in the psychoacoustic field with which National Physical Laboratory has been associated in recent years.

Scope of Investigation

Every audible pure tone can be represented, using its frequency and intensity as coordinates, by a point of the so-called auditory diagram. In this representation the equal-loudness contours are the loci of sets of such points representing tones of constant loudness. The set of all possible audible tones is represented by an area on the diagram which is bounded by the absolute threshold of hearing at the lower end of the intensity scale, and by the greatest intensities which the ear can tolerate at the other.

The frequency range over which the auditory area extends amounts to 11 octaves or more, though the boundaries between what is heard and what is perceived by other senses are somewhat blurred. A range of some 9 octaves from 25 to 15,000 cps was studied in the present investigation, and contains nearly all sounds of practical importance.

The new determination of the loudness relations was extended to include measurements of the threshold of hearing. A tone which is only just audible may be said to have just-zero loudness, and it would be expected that the curve of the hearing threshold as a function of frequency would itself constitute a member of the set of equal-loudness contours and form a natural zero for the set. The procedures for determining the hearing threshold of a tone and the loudness equality of pairs of tones are quite different, of course, but it turns out that the threshold values could have been predicted with considerable precision merely by extrapolating the equal-loudness relations.

[3] D. W. Robinson and R. S. Dadson, "A redetermination of the equal-loudness relation for pure tones," *Brit. J Appl. Phys.*, vol. 7, pp. 166–181; May, 1956.

We have not attempted to delineate the upper boundary of the auditory diagram. The onset of physiological effects with increasing intensity has formed the basis of a number of other studies. It appears that various phases may be distinguished (temporary loss of hearing, permanent damage, pain, and so on) which occur at levels covering a rather wide range of intensity. The thresholds of the phenomena are not determinable with the precision of the threshold of audibility and they are subject to extraneous factors, notably the duration of exposure. Our loudness experiments ranged up to sound pressure levels of 130 db above 0.0002 dyn/cm^2 in the low-frequency region, using tones of comparatively short duration (of the order of one second) in testing sessions lasting a few minutes, and our observers did not encounter appreciable physical discomfort or measurable fatigue.

In order to obtain sufficiently representative results, about 130 subjects of both sexes and ranging from 17 to 63 years of age were tested. These people were examined by an otologist to ensure that they would be classed from a clinical point of view as persons with unimpaired hearing. In the population at large there is naturally a proportion with hearing defects of every degree of severity. We regard this as a separate question and consider that a standard determination of the primary characteristics of hearing must be based on a group with unimpaired hearing.

A full description of the test procedures has been given[3] and will not be repeated here. We will only mention that the basis of our loudness tests was the so-called "method of constant stimuli." In psychological circles much is made of the contingency of the results on the test procedure. We believe that the method just mentioned eliminates difficulties of this kind. In outline, the listener hears pairs of tones and makes snap judgments of which member of the pair is the louder. By varying the intensity of one (or both) tones in a random manner between successive judgments, the point of *equality* of loudness emerges as the level at which a reversal of the *inequality* judgments occurs. Considerable precision is obtained in this way and the observer can gain no assistance from extraneous clues. The price to be paid for these advantages is the length of time required to complete a single observation.

Reference Conditions and Units of Measurements

From a theoretical standpoint the pure-tone equal-loudness relations may be considered as a surface in three dimensions representing respectively the frequency and sound pressure level of the tone, and the loudness. Thus, given any two of these quantities the third is determinate. Certain reservations are to be borne in mind here. The loudness of a pure tone is not determined wholly by the other two parameters but also depends on the listening conditions, and for this reason a set of reference conditions must be specified. Moreover, it is not a simple matter to attach numerical scale values to the loudness axis, though as a result of some recent work this step may now be taken with reasonable accuracy. We shall consider these two points separately.

Reference Conditions

The listening conditions adopted by Fletcher and Munson, Churcher and King, and in the present case, consist of listening with both ears to a source of plane waves (or approximately plane waves) situated directly ahead of the listener. In the case where the tone whose intensity is varied has a frequency of 1000 cps, these conditions amount to a determination of the loudness level of the other tone in phons, the value in phons being numerically equal to the sound pressure level (in decibels relative to 0.0002 dyn/cm^2) of the 1000-cps tone judged equal in loudness to the test tone in the opinion of a group of normal listeners. The concept of loudness level proves very convenient for the estimation of the loudness of all types of continuous sound, including of course pure tones, and many of the results in the present investigation were obtained by comparison with the 1000-cps tone in this way. In the particular case of pure-tone comparisons, however, there is no particular significance in according a special place to the 1000-cps tone, and a number of experiments were carried out with entirely consistent results by comparing pairs of tones of various frequencies.

Nevertheless, we follow the convention in presenting the results as though they had all been determined in terms of the 1000-cps reference tone, that is to say, as cross sections of a three-dimensional surface at equal intervals of the loudness level—the usual "equal-loudness contours."

The reference conditions outlined owe their origin to their freedom from ambiguity of definition and to their (comparative) ease of realization in anechoic conditions. This makes a satisfactory basis for the primary data but subsidiary experiments are required to relate the results to hearing under other conditions. For example, some determinations that are now nearly completed at the National Physical Laboratory give the relations between loudness under the reference conditions and for different directions of arrival of sound and for diffuse sound fields.

These results will be published separately in due course but they can be anticipated qualitatively here. The effect of expressing the primary equal-loudness contours in terms of the free field sound pressure in a normally-incident progressive wave is to introduce features in the contours specifically associated with the geometry of the human head. In a diffuse sound field these features tend to be less marked.

Scaling the Loudness Axis

In many applications it is enough to regard the contours as relations of equality, for example, as in treating the contours as frequency response curves of the ear for the purpose of "correction" by inverse weighting networks. It then is only necessary to label the relevant loudnesses by an arbitrary numbering scheme such as the phon scale; but, it must be remembered that the latter is a purely physical scale (proportional to the logarithm of a sound pressure) and takes no account of the phenomena of hearing. Some confusion has occurred over the nature of the phon scale because of its logarithmic character erroneously being identified with a supposed logarithmic action of the ear. So far as the sensation of loudness is concerned, the ear is decidedly not logarithmic in operation; it approaches more to a power law. But a determination of the exact relationship is necessarily a matter for subjective experiment and presents a number of difficulties. Many experimenters have worked on this problem including the author[4] and surveys of the data have been given recently in separate papers by Stevens[5] and the author.[6] The scale of relative loudness (sones) is most conveniently expressed by its relation to the phon scale because this is in principle an invariant transformation. Direct relations between the loudness and the physical intensity would vary from one sound to another according to the character of the sound.

The subjective experiments referred to are mainly of the type in which observers find the increment or decrement in the loudness level of a sound which doubles or halves its apparent loudness. Other numerical factors have been used with consistent results. An assessment of the various data[6] leads to the result shown in Fig. 1, from which can be deduced the natural scale for the loudness axis in a three-dimensional representation of loudness contours.

At a recent international meeting (ISO), it was provisionally agreed to adopt a simpler form for the sone/phon transformation; according to this proposal a two-fold loudness change is identified with a 10-phon change in the loudness level and the unit (1 sone) is fixed at 40 phons. This is recognized as an approximation, but it is attractive for practical purposes on account of its simplicity.

Redetermination of the Equal-Loudness Relations

Results of the redetermination of the equal-loudness contours are seen in Fig. 2; the curves were arrived at by smoothing the results of 141 measurements. Twenty-one of these were devoted to the threshold of hearing. In about 30 of the tests, a full team of over 120 persons took part, and the others represent results for a group of some 30 observers typical of the larger group. From

[4] D. W. Robinson, "The relation between the sone and phon scales of loudness," *Acustica*, vol. 3, no. 5, pp. 344–358; 1953.

[5] S. S. Stevens, "The measurement of loudness," *J. Acoust. Soc. Amer.*, vol. 27, pp. 815–829; September, 1955.

[6] D. W. Robinson, "The subjective loudness scale," *Acustica*, vol. 7, no. 4, pp. 217–233; 1957.

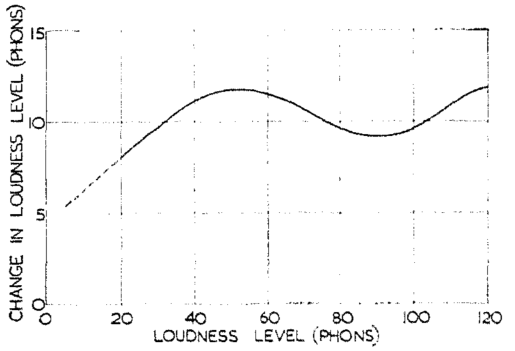

Fig. 1—Change in loudness level for twofold loudness change.

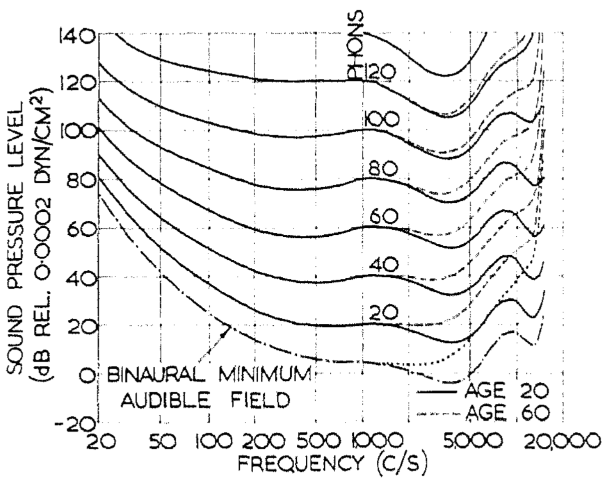

Fig. 2—Equal-loudness contours (Robinson and Dadson).

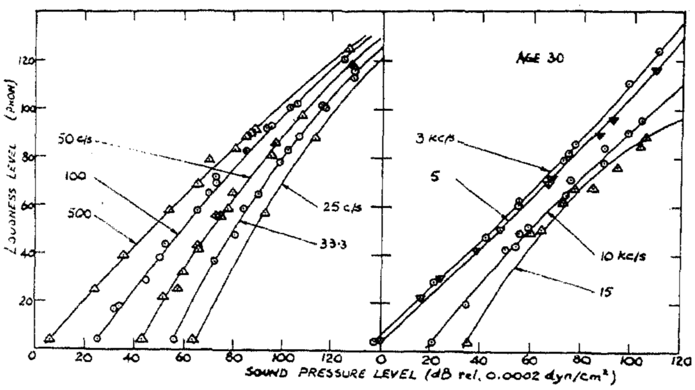

Fig. 3—Equal-loudness relations for typical frequencies.

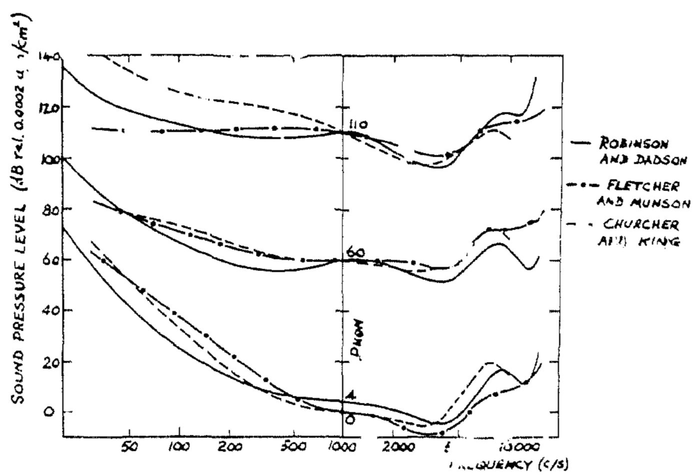

Fig. 4—Comparison of equal-loudness contours.

1000 cps up, the age of the listener is a significant factor and comes to dominate the result at 15,000 cps. Above this frequency the differences between observers even of the same age group would deprive a single value for the group of much meaning, and the experiments were terminated accordingly.

The loss of hearing with age (presbycusis) is discussed in another section, and in Fig. 2 we show only the results for ages 20 and 60 to avoid complicating the diagram.

The relations between loudness level and sound pressure level turned out to be very simple in form for frequencies over the whole audio range, which has enabled us to predict with some confidence the course of the relations slightly beyond the range of the measurements. A selection of the equal-loudness relations is shown in Fig. 3. They can be represented within the accuracy of the data points by equations of the second degree in the sound pressure level, thus enabling the complete results to be presented in short tabular form as a set of coefficients varying smoothly with the frequency. The appropriate tables are given in the original reference[3] and may be found convenient by some workers, especially in connection with loudness calculation in which it may be difficult to read from the graphical presentation with the required precision.

Over the greater part of the auditory diagram, including the threshold contour, the estimated accuracy of the smoothed data is 1 phon or better. Some reservation should be made regarding the values for 15,000 cps (because of the large individual variations), and the extrapolation from 25 to 20 cps.

Comparison with Earlier Results

General Features

Comparison of the general shape of the contours with the work of Fletcher and Munson and of Churcher and King is shown in Fig. 4 in which for clarity only a few contours have been shown.

The depression in the new curves centered on 400 cps was investigated closely by measurements under several different conditions and it was invariably confirmed. The new contours are less crowded in the bottom left-hand section of the auditory diagram than formerly, which is a reflection of the fact that lower threshold values have been obtained. In the upper left-hand section the results are intermediate between the earlier contours, and it should be noted that the new results are supported by experiment up to 130 db. whereas the earlier data relied heavily on extrapolation in this region. The trends of the various sets of contours towards the high frequencies are in some respects similar, and the magnitude of the discrepancies suggests that age effects alone might account for the greater part.

Threshold of Hearing

A significant feature of the new results is the fact that the normal threshold of hearing corresponds to a loudness level of 4 phons and not 0 phons as had been conventionally shown in the earlier work. A tone of loudness level 0 phons is audible to only about one person in eight and even less for high tones. For this reason we prefer not to show a contour through the zero of the loudness level scale.

In comparing the new threshold contour with the other data (Fig. 4), it should be noted first that the 0-phon contours shown by Fletcher and Munson and also by Churcher and King do not correspond exactly to their own measurements of the hearing threshold.

An example occurs in Table 3 of Churcher and King's paper in which sound pressure levels of 38.5 and 27 db are given for the thresholds of audibility at 54 and 120 cps, respectively. Corresponding values from the present investigation are 39.5 and 25 db (39.5 being an interpolated value) which are in much better agreement than would be suggested by inspection of the equal-loudness contours. It is also of interest that the threshold sound pressure level for the 1000-cps tone obtained by Fletcher and Munson was 4 db, in exact agreement with the present work and also with the classic work of Sivian and White[7] which will be referred to again shortly. It is curious that Fletcher and Munson, in deducing their set of smoothed contours, should have drawn their 0-phon contour sloping more steeply towards the low-frequency end than a curve through their own threshold values would run. This factor goes some way towards accounting for the apparent difference between their work and the new results.

Another interesting comparison can be made with the threshold values of Sivian and White. In this connection, there are two related sets of data which can be taken into account. Sivian and White found a difference, which remains unexplained, between the minimum values of sound pressure required to excite the sensation of hearing according to whether the sound is heard through an earphone or from a loudspeaker. Allowing for the fact that one set of data is for monaural and the other for binaural listening and also taking into account the distribution of interaural sensitivity differences (these two factors at most account for about 3 db), the free-field threshold pressure remains some 6 or 7 db below the threshold for earphone listening. Munson and Wiener[8] christened the effect the "missing 6 db" and its reality becomes apparent in various practical ways, for example, in the assessment of ear-defender performance.[9]

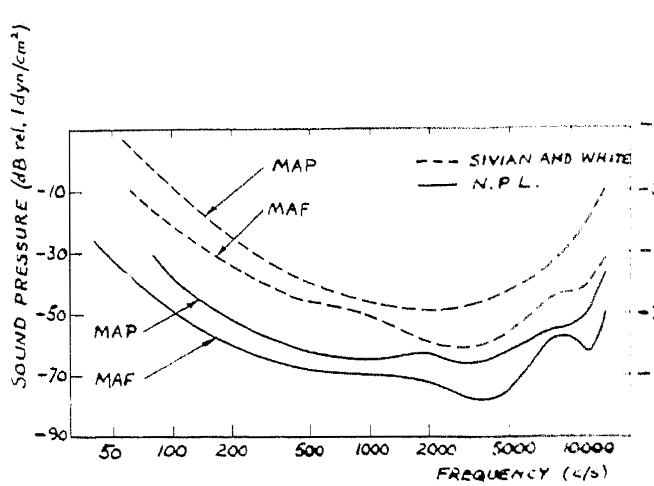

Fig. 5—Comparison of "minimum audible pressure" and "minimum audible field" curves.
Left-hand scale: NPL values. Right-hand scale: Sivian and White's values.

Taking the recent free-field threshold determination in conjunction with another investigation carried out at the National Physical Laboratory by Dadson and King[10] on the threshold by earphone listening, a striking confirmation of Sivian and White's effect is apparent. The corresponding pairs of "minimum audible field" and "minimum audible pressure" curves are illustrated in Fig. 5. In order to simplify the diagram, the curves of Sivian and White have been shifted upwards by 20 db.

At the lower frequencies the absolute values of threshold sound pressure are somewhat higher in the American work as compared with the recent British determinations; a factor which may be relevant is that the latter work was carried out in exceptionally silent conditions while Sivian and White and Fletcher and Munson made use of an open "sound stage."

Shape of the Equal-Loudness Relations

A feature of the loudness contours of Fletcher and Munson was the bunching of the intermediate contours at the low-frequency end. A typical equal-loudness relation taken from their paper is shown in Fig. 6(a). The bunching of the contours corresponds to the inflection in the figure. This trend is not supported by the new results, the corresponding relation (interpolated for 60 cps) being shown for comparison.

Towards the higher frequencies another change has occurred. Fletcher and Munson's curves indicate a progressive increase in the rate of growth of loudness level with the sound pressure level though this is not strongly supported by their experimental values. The present results conform to this trend from 1000 to 6500 cps but thereafter reverse. The difference becomes marked at 15,000 cps, at which the new results show a kind of saturation in the process of loudness growth [Fig. 6(b)].

[7] L. J. Sivian and S. D. White, "On minimum audible sound fields," *J. Acoust. Soc. Amer.*, vol. 4, pp. 288–321; April, 1953.

[8] W. A. Munson and F. M. Wiener, "In search of the missing 6 db," *J. Acoust. Soc. Amer.*, vol. 24, pp. 498–501; September, 1952.

[9] See for example, J. Hershkowitz, and L. M. Levine, "Attenuation of ear protectors by loudness balance and threshold methods," *J. Acoust. Soc. Amer.*, vol. 29, pp. 889–894; August, 1957.

[10] R. S. Dadson and J. H. King, "A determination of the normal threshold of hearing and its relation to the standardization of audiometers," *J. Laryngol. and Otol.*, vol. 46, pp. 366–378; August, 1952.

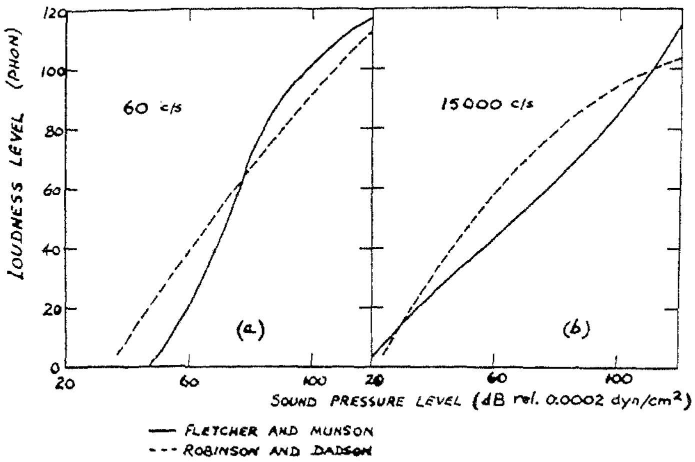

Fig. 6—Comparison of equal-loudness relations for 60 and 15,000 cps.

Accuracy of Loudness Measurements

When an observer is listening to a sound for the purpose of judging its loudness, it must be remembered that he is making an abstraction from the total perceived sensation, and it is a matter for experimental verification whether the quality abstracted is influenced by the character of the other sound with which the first is being compared. If this were the case, the importance of loudness as a measurable attribute would be gravely impaired, of course. During the course of the recent equal-loudness determinations a number of triangular comparisons were included, in which tones of three different frequencies were compared in pairs. Averaged over a group of some 30 observers the closure of these triangles was in each case accurate to the order of 1 or 2 db which is comparable with the standard error of the comparisons, and thus disposes of doubt as to the validity of the measurements.

The accuracy of laboratory loudness measurements is illustrated in Fig. 7 by way of correlograms. In each section of Fig. 7 the horizontal and vertical axes represent the loudness levels of a tone of given frequency and sound pressure level, as judged against the 1000-cps reference tone on two separate occasions separated by an interval of about three weeks. The coordinates of each data point are the respective values obtained by one observer, and the results shown are for a group of 28. The dispersion between the judgments of different observers is measured by the spread along the A direction, and limit lines are shown at ± 2 standard deviations about the mean. The accuracy of the individual measurements is measured by the spread in the B direction; limit lines corresponding to twice the error standard deviation are shown.

The point to notice is that the variability between observers is considerably the larger factor in each case. As would be expected, both components of the dispersion increase with the difficulty of the comparison, and in fact, are roughly proportional to the separation of the comparison tones in octaves.

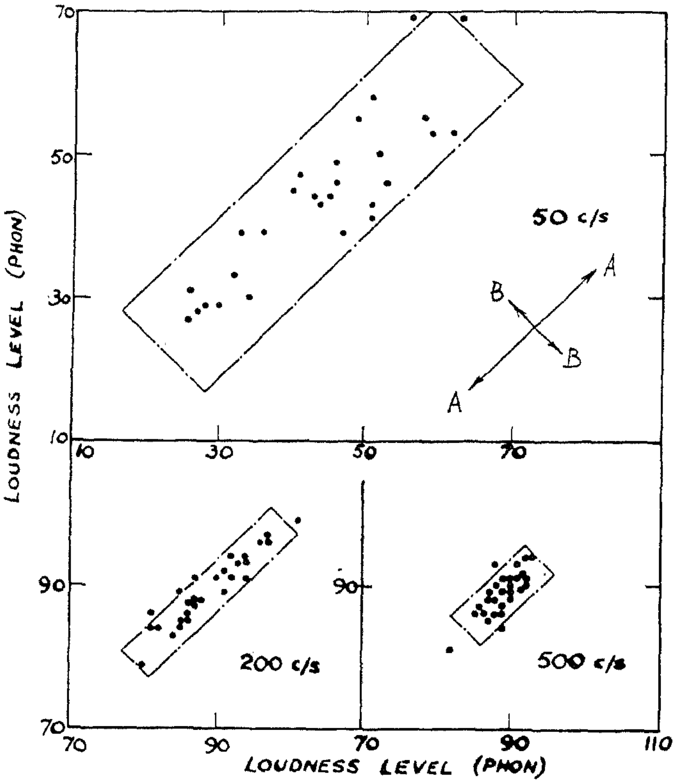

Fig. 7—Repeatability of measurements of loudness level of three pure tones by a group of 28 listeners.

The conclusion from these observations is that for a given expenditure of time a loudness determination preferably is carried out by a large number of observers making a single observation rather than by a smaller group making repeated measurements. And, as a corollary to this, once a loudness determination has been made by a group, little is to be gained by repeating it.

Similar conclusions can be drawn with regard to determinations of the hearing threshold. Fig. 8 shows correlograms for four repeated determinations by a group of about 100 observers, the interval between the tests being about 11 months in this case.

The Effect of Age upon Loudness

The separation of the loudness contours for widely separated age groups has been shown in Fig. 2 and it is convenient to discuss these results from two aspects: the raising of the threshold of hearing and the effect upon the loudness of supraliminal tones.

We are conscious, in presenting these results, of the comparatively small numbers of listeners in each age group but the consistency of several trends which we can distinguish gives some confidence that they are fairly representative.

With regard to the loudness of tones above the hearing threshold, the results at each frequency tested from 2000 to 15,000 cps showed that the loss of hearing, over a given span of years, diminishes appreciably as the intensity is raised. In the clinical literature this phenomenon is described as recruitment and is regarded as diag-

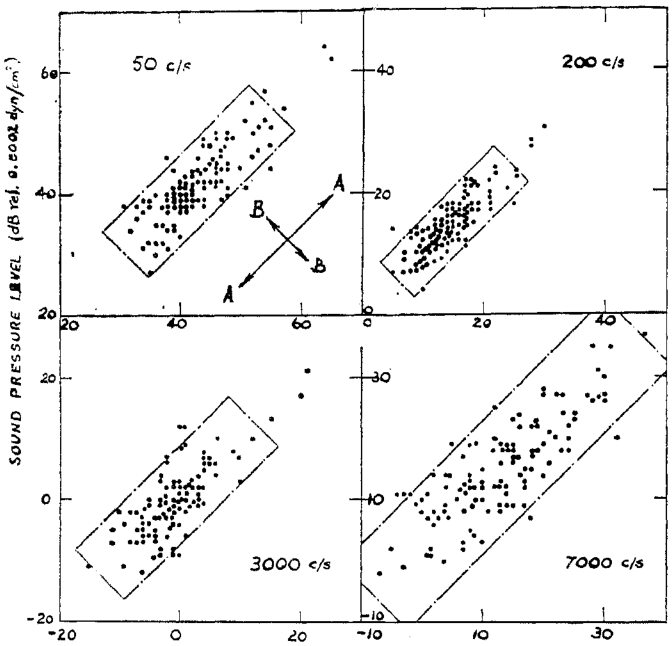

Fig. 8—Repeatability of threshold determinations at four frequencies by a group of about 100 listeners.

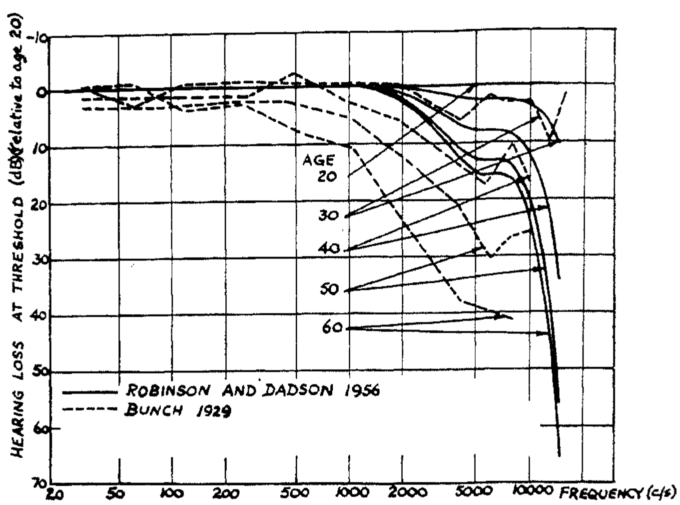

Fig. 9—Loss of hearing with age at threshold level.

nostic of certain types of nerve deafness. The present results refer, of course, to persons with ostensibly unimpaired hearing, and the degree of recruitment suggested by the data is in any case rather attenuated. Nevertheless it seems necessary to conclude that a mild degree of recruitment to high tones is a normal occurrence among older listeners. Moreover, it must be of binaural occurrence, otherwise the effect would be obscured by normal functioning of the better ear.

The rate of aging and the frequency dependence are illustrated best by reference to the raising of the threshold level. We found that the rise could be represented rather closely by the product of two factors, one depending only upon the age and the other only upon the frequency.

The variation with age seems to be steepest around 35 years and thereafter grows at a slower rate. The variation with frequency is negligible up to 1000 cps, and thereafter increases; the rate is greatly accelerated towards the upper frequency limit of the measurements. There is, however, a marked break in the upward trend around 5000 cps. This suggests a connection with the so-called "C⁵-dip" well known in audiometric circles. On the place theory of hearing it is supposed that tones in this frequency region stimulate maximum excursion of the basilar membrane at a section which is peculiarly susceptible to overload damage.

The results are shown in Fig. 9 in the form of audiograms relative to normal hearing at age 20, and are combined with presbycusis curves based on the well-known work by Bunch.[11] The latter data apply to a very much larger group of subjects; on the other hand the subjects were hospital patients not necessarily in good health, which can account for the poor agreement with our data in absolute magnitude. There is a general similarity with regard to the frequency dependence in both sets of results.

Comparison of Results for Male and Female Listeners

The classification of the results of the loudness and threshold determinations by sex showed only small differences between group averages. Below 1000 cps they were negligible or unsystematic, but for the higher frequencies a consistent trend was apparent, as indicated by the open circles on Fig. 10.[12] The magnitude of the difference remains comparatively small, however, and in presenting the equal-loudness contours we have not considered it necessary to make a distinction.

On the other hand, an inquiry into the origin of the observed systematic differences at higher frequencies leads to interesting conclusions. In their paper on the threshold of hearing by earphone listening, Dadson and King[10] remark that systematic differences were not apparent at any frequency between the results of male and female subjects. This suggests that the results in Fig. 10 may be attributable to unequal diffraction by male and female heads in the reference sound field, and this turns out to be well supported by direct experimental evidence.

In connection with another study we have measured the "obstacle effect" of some 46 heads (24 male and 22 female) in the reference sound field over a wide frequency range. For this purpose a probe tube microphone was employed, and the results are expressed in terms of the ratio of the sound pressure at the entrance

[11] C. C. Bunch, "Age variation in auditory acuity," *Arch. Otolaryngol.*, vol. 9, pp. 625–636; 1929.

[12] The data points shown are averaged over the threshold test and loudness tests at various intensity levels at the frequency shown. The values, though small, must be considered systematic, bearing in mind the large number of observations compressed into each point in Fig. 10.

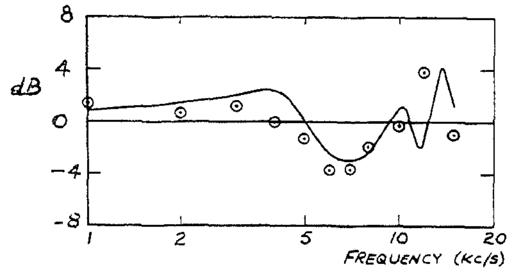

Fig. 10—Average loudness level difference for male and female listeners as a function of frequency.
⊙ Average values from loudness and threshold determinations.
— Difference between diffraction effects of male and female heads.

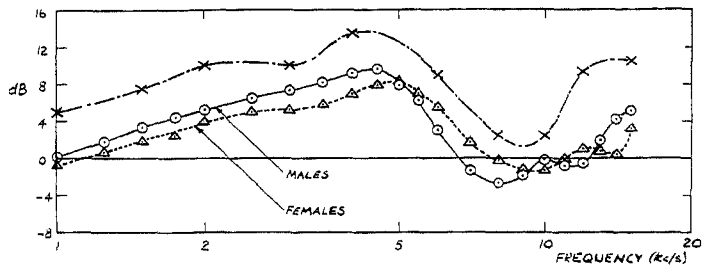

Fig. 11—Effect on reference sound field due to presence of listener's head.
⊙ Mean experimental results on 24 male heads.
△ Mean experimental results on 22 female heads.
× Difference between pressure and free field thresholds.

to the right external auditory meatus to the free field sound pressure in the progressive plane wave. Average results for the male and female groups are shown in Fig. 11. Each curve exhibits two maxima and two minima; moreover, the corresponding critical frequencies are in almost a constant ratio (about 1.15 to 1) which would be entirely consistent with an average difference in linear dimensions of male and female heads of this amount. It is interesting to remark here that measurements of the intramastoidal distance of 100 heads (which were made in another connection) gave average results of 13.6 cm and 12.4 cm for male and female heads respectively, which supports the previous argument.

That these geometrical considerations are probably sufficient explanation of the observed differences between the mean loudness judgments of male and female listeners is shown by the continuous curve in Fig. 10 which is merely a plot of the difference between the two lower curves in Fig. 11. We conclude there are no inherent differences in the hearing processes of men and women.

Finally it is interesting to consider the frequency dependence of the "missing 6 db." As has been seen, the "minimum audible field" curve is affected by head diffraction while the "minimum audible pressure" is not, of course. The difference between these curves thus would be expected to show the features characteristic of the "obstacle effect," and this is demonstrated clearly by the upper curve in Fig. 11 which is a plot of the difference between the lower curves of Fig. 5. The undulations of the "missing 6 db" are thus well accounted for, and we appear to be left with a residue which is more or less independent of the frequency.

Acknowledgment

The author wishes to acknowledge the cooperation of the members of the Laboratory staff who took part in the various phases of the investigations described, and the collaboration of R. S. Dadson with whom the greater part of the work was first published jointly.