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REVIEW OF RESEARCH AND METHODS FOR MEASURING THE LOUDNESS AND NOISINESS OF COMPLEX SOUNDS

by Karl D. Kryter

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BOLT BERANEK AND NEWMAN, INC.
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for

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SUMMARY

A detailed review of the research and concepts underlying the evaluation of the subjective attributes of the loudness and noisiness of complex sounds is presented. Knowledge about the attribute of loudness has reached the stage where two procedures for the calculation of the loudness of a complex sound from purely physical measurements (octave, one-half octave, or one-third octave band spectra) have been proposed for standardization on an international basis. The methods are those proposed by Stevens and by Zwicker.

It is proposed that the perceived noisiness or "unwantedness" of a sound is more important to the evaluation of man's noise environment than is loudness. The following physical and temporal aspects of a sound, listed in order of importance, have been found to influence how people will in general rate its subjective noisiness: 1) intensity level, 2) spectrum shape and bandwidth, 3) spectral complexity (presence of one or more pure tones in a band of random noise), and 4) duration. Various methods have been developed for calculating the perceived noisiness of complex sounds from either one-third octave or full octave band spectra. National and international standards have been proposed to use perceived noise level in PNdB for the evaluation of aircraft noise. Additional procedures are tentatively proposed for modifying calculations of PNdB levels to take into account the effects of pure tones and duration upon the perceived noisiness of complex sounds.

INTRODUCTION

With the advent of problems related to increased dissatisfaction with noise in the community, home, and office, acoustical engineers and psychologists suggested that the ranking or rating of the acceptability of real-life sounds be made in terms of their loudnesses. The tacit assumption was made that, other things being equal, the louder a sound is, the more unacceptable it is. While this is undoubtedly true, it overlooks the possibility that other basic attributes of a sound, such as pitch, complexity, etc., might interact with loudness to produce

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different judgments of acceptability than loudness alone. Indeed, as we shall see later, such an interaction does apparently take place.

In order to review the research leading up to the present methods for measuring the noisiness of complex sounds, we first review some of the concepts and studies underlying the development of methods for rating the loudness of sounds. Following this we present a similar review associated with the methods for rating perceived noisiness. Finally, the results of judgment tests for validating some of the methods for estimating loudness and noisiness are described.

LOUDNESS

There are three basic relations (ignoring temporal factors) to be established before one can adequately depict the perceptual attribute called "loudness" in terms of physical aspects of the acoustic stimulus:

1. What is the relative loudness of tones of frequency bands of sound of different frequencies, i.e., what adjustments in intensity levels, if any, are required to make each tone, or band of frequencies, in the audible frequency range appear to be subjectively equally loud to each other?

2. How does loudness grow as the bandwidth of the sound spectrum is widened, i.e., as one adds together several tones or narrow frequency bands of sound that are equally loud, what happens to total loudness?

3. What is the functional relation, for a given sound, between sound pressure level and loudness, i.e., at what rate, upon some numerical scale, does the loudness of a sound grow as its physical intensity is increased?

The Dependence of Loudness on Frequency

Fletcher and Steinberg (ref. 17), Steinberg (ref. 92) and Fletcher and Munson (ref. 18) appear to have made the first major attempts to define and measure loudness. Fletcher and Munson defined loudness as the "magnitude" of a sound and assumed that the loudness was proportional to the number of impulses leaving the cochlea upon stimulation. Fletcher and Munson specified a 1000 cps tone as the standard sound against which other tones would be judged for loudness. Stevens (ref.93) later suggested that the unit of loudness be called the sone, and that one sone be ascribed to a 1000 cps tone set at a sound pressure level of 40 dB.* The sone scale, which will be discussed more fully later, is such that a sound twice as loud as a sound of 1 sone is given a value of 2 sones, four times as loud is called 4 sones, etc.

Equal loudness contours. - Fletcher and Munson (ref. 18) found the sound pressure levels required for pure tones over most of the frequency range in order that they be judged equal in loudness to a 1000 cps reference tone set at a specified sound pressure level; the results are called equal loudness contours for pure tones.

A number of other investigators have also determined equal loudness contours for pure tones as well as bands of noise, using a tone or band of noise centered at 1000 cps as a reference sound against which other sounds are judged. Stevens (refs. 94, 95) summarized the work of these investigations and also determined equal loudness contours for tones and bands of noise.

The various loudness contours have their differences and their similarities as shown in figure 1. Robinson and Whittle, who have made careful studies of the loudnesses of pure tone and octave bands of noise, recently proposed that the differences, at least for the octave band contours, be reconciled by simply averaging the contours obtained by Stevens (ref. 95), Cremer et al (ref. 11), Robinson and Whittle (ref. 87), and a set of contours calculated according to a method recently proposed by Zwicker (refs. 108, 109) (to be discussed below). For most loudness levels the empirically determined loudness level contours (Stevens, Cremer et al, and Robinson and Whittle) agree with each other reasonably well. Zwicker's calculated contours tend to diverge from the others. The result of the averaging proposed by Robinson and Whittle is shown in figure 2. Jahn (ref. 35) has published data, for a few subjects who judge the

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* Throughout this document sound pressure levels will be expressed in decibels (dB) re 0.0002 microbar, where

$$dB = 20 \log_{10} \frac{\text{Pressure}}{\text{Pressure}_{\text{ref}}}.$$

loudness of some octave bands of noise at low loudness levels, that agree fairly well with the Robinson and Whittle averaged contours.*

Investigators have attempted to find "correction" factors that can be used for converting equal loudness contours obtained with frontal incident sound in a free (acoustically non-reverberant) field and those obtained in a more or less diffuse or reverberant room. The latter condition, while somewhat harder to specify acoustically, is probably more representative of everyday listening conditions. Figure 3, taken from Robinson and Whittle (ref. 87), shows the differences found, as a function of frequency, between these two listening conditions.

Stevens' method for the calculation of loudness. - Equal loudness contours whether for pure tones or bands of noise are of somewhat academic interest unless they can somehow be used for evaluating the loudness of complex noises and sounds found in real life. Steinberg, and later Fletcher and Munson, proposed a procedure for calculating from physical measurements the loudness of a complex sound consisting of a number of tones. Their method, however, was not much used because of its complexity, plus the fact that the sounds of greatest practical interest tend to be broad-spectra sounds and not pure tones.

Gates [comments in paper by Churcher and King, (ref. 8)] and later Beranek et al (ref. 2) proposed that a simple summation of the loudness in sones of octave bands of sound (it was assumed that an octave band of random noise having the same overall SPL as a pure tone of the same center frequency would be equally loud) would give a reasonable approximation to the perceived loudness of a complex sound consisting of one or more octave bands of random noise. In addition to the equal loudness contours for octave bands of random noise, Stevens (refs. 95,97) also published new procedures to be used for evaluating the total loudness of broad, continuous spectra sounds. Stevens demonstrated that his method was more accurate in predicting the judged loudness of complex sounds consisting of bands of random noise than the method of simply adding together the sone values of individual bands.

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* Pollack (ref. 69) obtained equal loudness contours for bands of noise using a reference or standard sound broadband white noise from 100 to 10,000 cps instead of a narrow band centered at 1000 cps, used as the reference sound in the other investigations of equal loudness contours of bands of noise mentioned above. Pollack's contours tend to be somewhat "flatter" than the contours found when the reference sound is a tone or band of noise centered at 1000 cps.

Stevens' general formula is to add to the sone value of the loudest band a fractional portion of the sum of the sone values of the remainder of the bands:

$$\text{Loudness} = S_m + f(\Sigma S - S_m)$$

where ΣS = sones in all bands, S_m = maximum number of sones in any one band, and f = fractional portion dependent on bandwidth.

Stevens derived the fractional portion to be applied when the spectra of the sound was measured in either full ($f = 0.3$), one-half ($f = 0.2$), or third ($f = 0.15$) octave bands.

Stevens (ref. 99) slightly modified his method of calculating loudness and named this new method "Mark VI." Mark VI has been adopted by the American Standards Association as the procedure to be used for the calculation of loudness of noise measured in either octave, one-half octave, or one-third octave bands. The procedures and formulae for the calculation of loudness, Mark VI, is the same as that in the Stevens' 1957 article, except that individual band values of loudness are found from a graph depicting loudness index (I) contours that are slightly different than equal loudness (sone) contours.

As aforementioned a tone that is the same loudness as a reference tone of 1000 cps is given a value of 1 sone when the reference sound has a sound pressure level of 40 dB re 0.0002 microbar. In the original Stevens' (1957) procedure for calculating the loudness of bands of noise, the bands of noise were equated to this 1000 cps reference tone -- for example, the octave band 600-1200 cps at a sound pressure level of about 38.5 dB has a loudness of 1 sone; in the Mark VI modification the same band at 34.5 dB is given a loudness index of "1," which is equivalent to 1 sone.

It has become practice, however, to express the loudness of a sound in terms of the sound pressure level in dB of the reference sound rather than in units of loudness, or sones. The result is called loudness level in "phons," the word phon being used in place of the mathematically equivalent decibel to indicate that this unit is a ratio which has been derived from psychological units, sones, and not directly from physical measurements of sound pressure; further, the phon is obviously not, as defined above, $20 \log_{10}$ of the ratio of two loudnesses, as the decibel, when applied to sound pressures, is $20 \log_{10}$ of the ratio of two sound pressures.

The International Organization for Standardization (ISO) has recommended Mark VI as the method to be used for calculating the loudness of sounds measured with octave band filters and Zwicker's method (to be described below) when the sounds are measured with 1/3 octave band filters (ref. 33).

Zwicker's method for calculating loudness. - As aforementioned, Fletcher and Munson suggested that loudness is proportional to the number of nerve impulses per second reaching the brain from the excited auditory nerve fibers. Further, they noted that the masking of one tone by another would interfere with simple loudness summation and that it must be necessary to "group together all components within a certain frequency band and treat them as a single component," and that the width of these "grouping together" bands is estimated to be 100 cps for frequencies below 2000 cps, 200 cps wide between 2000 and 4000 cps and, 400 cps wide between 4000 and 8000 cps.

From subjective tests of loudness and masking, Zwicker, Flottorp and Stevens (refs. 107,112) determined the frequency groupings "frequenzgruppen," that take place in the cochlea of the ear (see Table 1); these frequenzgruppen are sometimes referred to as "critical bands."

Zwicker determined the spread of masking for narrow bands of noise, the threshold of audibility of pure tones, and the change in level of a 1000 cps tone to obtain a doubling (or halving) of loudness. His results on the growth of loudness are similar to those found by Stevens (ref. 96) and Robinson (ref. 82); his data for spread of masking for narrow bands of noise are more or less, as far as can be determined from his published results, like the spread-of-masking data obtained by Egan and Hake, (ref. 12) and Carter and Kryter (ref. 6). Zwicker's assumption that there is a functional correspondence between masking and loudness is well substantiated by data on the critical bandwidth of the ear.

Zwicker, on the basis of these concepts, developed a very direct and ingenious method for depicting and calculating the loudness of a complex sound (refs. 108,109). For calculation purposes he prepared ten graphs (ref. 109) (covering both diffuse and free field conditions) similar to the sample shown in figure 4 in which the abscissas were marked off in equal frequenzgruppen (approximated for practical purposes by 1/3 octave steps above 280 cps), and the vertical divisions for each 1/3 octave are, in loudness units, proportional to sones. The short-dashed curves in figure 4 show the area covered by the upward spread of masking.

Plotting a sound spectrum on Zwicker's graph and drawing in the lines for spread of masking are supposed to show, in essence what proportion of available "nerve impulse units" are made operative as the result of exposure of the ear to a given sound; accordingly, this area on the graph is proportional to total loudness. A planimeter is supposed to be used for measuring the area encompassed by a given sound as plotted on one of Zwicker's graphs, although the area can also be estimated with reasonable accuracy by visual inspection of the area of the plot.

Zwicker defines as 1 sone the area encompassed on his graph by a one-third octave band of noise centered at 1000 Hz (cps) at a sound pressure level of 40 dB including the additional area encompassed by the dashed curve that takes into account the upward spread of loudness (masking).

It should be noted at this point that in Stevens' Mark VI method, either a one-third octave or full octave band of noise centered at 1000 cps at a level of 34.5 dB would have a loudness index of 1.0. We shall see in a later section of this report that because of this and other difference between the Stevens and Zwicker methods, the loudness levels calculated by the two procedures for the same sound often differ by 3 to 5 phons.

Zwicker's model is straightforward and consistent with experimental fact. Further, it does, as we shall see later, very well in predicting the relative loudness of a wide variety of complex sounds. However, because it requires in its execution the plotting of 1/3 octave band data on special graph paper and, for greatest accuracy, the use of a planimeter to measure the loudness area, Zwicker's method has some practical disadvantages for general use.

Munson's method. - Munson (ref. 58) has proposed a modification of the "equivalent-tone-sone summation" method suggested by King, Gates, and Beranek et al, to take into account the spread-of-masking and loudness effects that are acknowledged in Stevens' and Zwicker's schemes for calculating loudness. Munson's procedure as he states, is not based on any published theoretical model or experimental data and perhaps loses some appeal for that reason; in any event the procedures proposed by Munson are not as yet widely used or validated.

The Dependence of Loudness On Intensity (Growth of Loudness)

The studies concerned with loudness evaluation discussed to this point have been concerned primarily with the loudness of individual pure tones or narrow bands of noise of different frequency, relative to the loudness of the "standard" 1000 cps tones and the loudness of several pure tones or bands of noise heard together, i.e., the effect of variations in total bandwidth of a complex sound upon judged loudness. By and large, although there are differences in equal loudness contours found by various investigators, their shapes are in reasonable agreement.

Also, although Zwicker's method for handling the bandwidth factor is different than that developed by Stevens, except for a constant difference of about 4 dB, the results obtained by these two methods of calculating the relative loudness, as will be seen later, are not too different for sounds having rather broad, continuous spectra.

On the other hand, scaling the growth of loudness of sound into psychological units of equal subjective value has been a much more controversial problem. Excellent reviews of this work in this area have been made by Stevens (ref. 98) and Gzhesik (ref. 30).

There have been three general methods used for scaling the growth of loudness of a sound, usually a 1000 cps tone, as a function of changes in sound pressure level which are:

1. Monaural vs Binaural Loudness
2. Magnitude and Ratio Estimation
3. Equal Section or Equal Interval

Monaural vs binaural loudness. - The argument of the method used by Fletcher and Munson, which followed from their assumption that loudness was proportional to the number of auditory nerve impulses reaching the brain, was that the same sound delivered to the two ears should appear to be twice as loud as when presented only to one ear. Fletcher and Munson found that the level of the monaurally presented tone had to be set about 10 dB higher in level than the level of a binaurally presented tone. Thus, they concluded that over at least the middle range loudness levels, subjective loudness about doubles for each 10 dB increase in the sound pressure level of a sound.

Reynolds and Stevens (ref. 77) found that the loudness scale for monaural listening was somewhat different than the loudness scale for binaural listening, indicating that the Fletcher and Munson assumption about the summation of loudness from the two ears was less than perfect at least at some levels. However, Hellman and Zwislocki later found nearly perfect, within experimental error, interaural summation of loudness, as shown in figure 5.

Magnitude and ratio estimation. - Although some doubt the general validity of the assumption of the addativity of loudness from the two ears in terms of number of nerve impulses, the monaural vs binaural equal loudness scale is very similar to the average of those developed later on the basis of magnitude estimations of loudness. In this latter method the subjects assign a number, say 100, to a tone at, say, 100 dB SPL; they are then asked to assign the number 50 to the tone when it sounds half as loud as it did at 100. Another method of estimation is that of estimating loudness ratios or fractions (ratio estimation or judgment); here the subjects may adjust the level of a tone until it is, say, one-half or one-tenth, or twice, etc.) as loud as a standard of reference level.

Results of studies by various investigators using the magnitude estimation and ratio judgment methods differ rather widely. Garner (refs. 25,28) believes the differences among the results of experiments on judgments of loudness fractions (ratio judgments) are due in part to "context effects." That is, a loudness judgment depends on whether or not the subject knows the full range of levels available to him (a subject will give different judgments about what appears half as loud when he knows the total range of levels available to him for judgment, than when he does not). In most studies of loudness fractionation, the minimum or zero loudness is assumed to be threshold of hearing, a rather inexact and individualistic value that would change the general "context" of level range available to different listeners.

Garner (ref. 28) was able to train different groups of subjects (a training period plus 600 experimental trials) to state that half-loudness of a 90 dB tone was either 60, 70, or 80 dB depending on the range of intensities available to each group as a choice for half-loudness. These results, however, have perhaps as much to say about the effects of training as they do about the effects of context upon magnitude estimation of loudness.

A second and possibly more important factor than context influencing the results of studies in which people estimate loudnesses, is that different people apparently have different "rules" they follow when making ratio or "fraction" judgments. Evidence of this variability in individual loudness function was found by Garner (ref. 24) by the method of fractionation (one-half), as shown in figure 6.

A third factor, probably not unrelated to the second above, that has caused some difficulty and variability in loudness estimation, is that numbers apparently have semantic meaning beyond their strict arithmetic character. Hellman and Zwislocki (ref. 31), using the method of magnitude estimation, obtained results that suggest that the number 1, for example, was appropriate for the loudness of a 1000 cps tone at 40 dB, and 10 for a level of about 70 dB as indicated in figure 7. Figure 8 shows the different loudness scales found when the number 10 was assigned by the experimenter to different reference sound pressure levels.

Stevens (ref. 98), in reviewing loudness scaling procedures, makes the point that although obtaining a loudness scale from a listener is a difficult problem, it is a function that must be determined if the concept of loudness is to have any practical utility. Apparently, as Stevens suggests, the best method (called magnitude production) is to allow each subject in such experiments to use whatever number scheme he wishes and to then average results across subjects after normalizing the results for individual differences in the choice of numbers used.

Equisection loudness scale (equal intervals). - In addition to the one-ear vs two-ear, and the methods of magnitude and ratio estimation, a method of equal intervals or equisection has been suggested as a suitable method for deriving a scale of loudness. In this method, the subject hears a tone presented at, in the simplest case, two different levels of intensity; he is then told to adjust the third level of the same tone such that the difference in loudness between the second and third levels is equal to that between the first and second intervals. Using this method, Wolff, Kwiek and Garner measured equal intervals over various ranges of intensity of a 1000 cps tone.

Unlike the magnitude and ratio estimation methods, the results obtained by various investigators using the method of equal intervals are in close agreement with each other. However, there is no real knowledge obtained from the equal interval method as what changes in level are required in order that the listener report a subjective sensation of the doubling, or halving, or some other fraction in the loudness of a sound.

Garner concluded that loudness scales based on ratio judgments and magnitude estimations are too inconsistent among different subjects to be meaningful. Instead, Garner derived a loudness scale from judgments of equal loudness intervals found by the equisection procedure.* The results of a series of equal-interval tests are shown in figure 9.

Garner's problem was to combine these loudness scales, each of which covers but a small segment of the total audible intensity range, into a scale that runs from zero to maximum loudness. He combined the curves in figure 9 into a single loudness function, shown in figure 10, on the basis of the following argument and procedure:

> "In order to put all the sections together, we have to determine the equivalence in loudness between the various ranges of loudness levels. We know that the loudness represented by a loudness-level range from 70 to 90 phons is the same regardless of whether that range occurs in the curve representing loudness levels from 50 to 90 or 70 to 110. In the plot of figure 9, the 70 to 90 range has been assigned a loudness of 2.12 units (from 2.9 at 70 dB to 5.02 at 90 dB) on the right-hand curve. On the curve next to it, this same loudness-level extent has a loudness of 3.90 units. In order to assign equivalent values to both sections of the curve, we must therefore multiply all values of the second curve by 2.12/3.90, which equals 0.543. In addition, we have to move the entire curve down until it fits the same range of loudness values as the first section. Thus, we have essentially adjusted both the slope and intercept constant of this second section to make loudness values over the same range of loudness levels agree. Once this has been accomplished, a similar process fits the third section into the first two, and the fourth section into the first three."

Garner determined, by graphic and algebraic means, the true zero point and the arbitrary constant present in the function shown in figure 10, and was then able to plot the average loudness function shown in figure 11. Also shown in figure 11 are

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* Although words like "one-half," or "twice," or a numbering scheme are not included in the instructions to the subjects, the method of equal intervals or equisection is in the last analysis a special case of magnitude estimation where the subject is presented with a very restricted range of intensities he is asked to bisect. And the repeatability of the experimental findings of various investigators may be as much due to this restricted range of levels involved in any one set of judgments as it is to the unambiguousness of the task assigned to the listeners.

the loudness function found by Fletcher and Munson using the one-ear vs two-ear method, and the average loudness function proposed by Stevens and Hellman and Zeislocki on the basis of ratio and magnitude estimation experiments.

Garner suggests that although each listener can consistently estimate loudness, the numerical scale he uses is not necessarily the one that he was asked to use by the experimenter. Garner proposes a set of mathematical operations whereby one can derive the actual scale used by the listener.*

Inasmuch as the loudness scale derived by the equal-interval method is so different from the scales derived by other methods (see figure 11), we must choose one or the other for practical use. It would seem reasonable to decide which of these forms of loudness functions is to be used on the basis of how the loudness scale is to be used. If, for example, it is intended to say that sound "A" is twice (or some portion) as loud as sound "B", then we are obliged to use a loudness scale based on ratio or magnitude judgments. On the other hand, if we want to decide whether the difference in loudness between sound A and B is equal to the difference in loudness between B and C, then the Garner-Kwiek loudness scale would be more meaningful. The fact that these two types of loudness scales are reconcilable by the Garner-Ghezik calculations is helpful evidence that we are dealing with the same attribute of sound, namely, loudness, but it does not let us say which method of determining the loudness scale is the "correct" one.

If, and we would assume that such is the case, the general interest in loudness judgments in real-life situations is more in terms of apparent magnitude or relative loudnesses than in terms of equal intervals, it would seem that we must accept the equal loudness scale based on magnitude estimation as being the more applicable for general use.

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* From Garner's hypothesis, but first converting the loudnesses into logarithmic units, Gzhesik et al (ref. 30) derived and calculated what apparent ratios were actually used by the subjects in the various experiments involving ratio judgments of loudness. Except for a few experiments that include questionable data, it was found that the "corrected" ratio indicated that the typical listeners divided the loudness by a factor of about 1.5 instead of 2 when instructed to halve the loudness of a tone. Gzhesik found a close similarity between the Kwiek and Garner type of loudness function and the Stevens and Fletcher and Munson loudness scales when the latter were "corrected" for ratio and point of origins.

Changes in Loudness with Time

For the most part loudness judgments have been made only of sounds having durations of from fractions of a second to several seconds long. According to Miller (ref. 53) loudness presumably remains more or less constant after the first 100-200 milliseconds of duration of a sound. There are, of course, some exceptions to this generalization. For example, Elliott reports there is an apparent growth or "flutter" in the loudness of bursts of noise repeated over a period of 20 to 320 seconds (ref. 13).

Taub and Teichner (ref. 101) find that a 2-3 dB increase in the loudness of a tone and band of noise having a level of 90 dB during a 10 minute exposure; however, there was a decrease of about 5 dB in the loudness of the combination presented at 70 dB for 10 minutes.

Although there are no obvious explanations for these phenomena (both Elliott and Taub and Teichner postulate central nervous system or perceptual theories) it is possible that the aural reflex may be at least partly responsible. Elliott finds a greater effect for a 73 dB level where the reflex should possibly be partly activated than at a 53 dB level where the reflex would not be activated; and in the Taub and Teichner experiment one would expect the reflex to be subsiding at the end of a 10 minute exposure to a 90 dB noise and possibly was becoming activated after a 10 minute exposure to a noise at 70 dB.

Continued exposure to a steady-state sound produces another change in loudness that normally goes unnoticed by the listener. It is most striking when one ear is exposed and the other ear is not exposed to an intense sound. When both ears are then subsequently exposed to the same sound, the loudness in the previously unexposed ear is greater than in the previously exposed ear. The effect has been called per-stimulatory fatigue. It is not clear whether the effect is due to receptor fatigue or to a purely perceptual loudness adaptation, or to both.

Loudness Measured by Sound Level Meters

Although the loudness of a complex sound is presumably best estimated on the basis of band spectrum analysis data, the simple sound level meter that integrates acoustic energy over the audible spectrum to achieve a single overall value is widely used for this purpose.

The present standardized sound level meter can be operated in three modes:

1. with a network that, more or less, weights the intensity value of the frequency components in a sound in accordance with the shape of the Fletcher-Munson equal loudness contour at the level of 100 phons -- this is called the "C" scale;

2. with a network that weights the frequency components more or less in accordance with the 70 phon contour -- the "B" scale; and

3. with a network that weights the frequency components more or less in accordance with the 40 phon contour -- the "A" scale.

Sound level meters give readings in decibels relative to 0.0002 microbar, integrating (with an integrating time constant of 0.2 seconds) the sound pressure over all frequencies from about 50 to 20,000 cps. This report will designate sound level meter readings taken with the various weighting networks as dB(A), dB(B) and dB(C) as appropriate. In the general literature, and in this report, when sound pressure levels are reported as unqualified "dB" values, it is to be understood that the weighting network of the meter was set on C or a "flat" equal-frequency-weighting scale.

When used with individual pure tones, one would expect the sound level meter to give reasonably good estimates of loudness. One might feel, however, that this would not be true for more complex sounds. Nevertheless, as will be demonstrated later, when the network with 40 phon weighting is used with broadband sounds in the region from perhaps 60 to 100 phons, the obtained reading agrees reasonably well with judgment data of the loudnesses if the energy of the sounds is concentrated in the frequency regions below 500 cps or so, or above 2000 cps or so. The validity and use of the sound level meter with weighting networks for the evaluation of noises will be discussed below.

A meter involving a set of octave band filters and various other electronic circuits that will automatically give loudness level in phons as would be found by the Stevens (ref. 97) method of calculating loudness has been developed by Anderson (ref. 1).

PERCEIVED NOISINESS

In 1958 a series of tests was conducted in which subjects individually adjusted the sound pressure level of a recording of the flyover sound made by one type of jet aircraft until it sounded as acceptable or "noisy" to each of them as the sound of another type of jet aircraft, or the sound of a conventional propeller-driven aircraft, if they were listening to it in or near their home.

It was obviously impractical to attempt to obtain from listeners in the laboratory judgments for all aircraft types, operational flying conditions, distances from the aircraft, etc. What was needed was a procedure whereby one could directly measure with a meter, or calculate from physical acoustical measurements, what was the relative noisiness or acceptability of all types of aircraft sounds. The specific question at hand was whether the sound from future commercial jet aircraft would be more or less bothersome to communities near airports than the sound from propeller-driven aircraft then in operation.

These experiments showed that sound level meter readings on A, B, and particularly C scales, and loudness level in phons calculated by Stevens' method, did not predict the judged noisiness of the sounds as well as was desired.

Some experiments had been performed in 1943 at the Harvard Psychoacoustics Laboratory under the direction of Professor S. S. Stevens to pursue the earlier work of Laird and Coye (ref. 49) on the "annoyance" values of sounds of different frequency. The data as reported by Reese, Kryter and Stevens (ref. 76) showed that the higher frequencies tended to be more annoying than the lower frequencies even though they were equally loud.

Although the data in the 1943 experiment was rather meager, they were renamed "equal noisiness contours" and used by Kryter (ref. 38) in an attempt to predict the results of the aforementioned tests with aircraft noise.* This was done by modifying Stevens' equal loudness contours for octave bands of noise to take into account this additional contribution made by the higher frequencies to the subjective acceptability or noisiness of complex sounds. Utilizing without change the remainder of Stevens' method for calculating loudness, one proceeds to calculate what was called the relative "noisiness" or "unwantedness" of complex sounds. To distinguish the modified loudness

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* Kryter and Pearsons (ref. 42) later obtained further and rather extensive data on "equal noisiness" contours which they proposed be used in place of the contours obtained in 1943.

contours from the regular loudness contours and the resulting units from loudness terminology, it was proposed that the unit of noisiness be called the "noy" in parallel to the "sone" for loudness; one noy was defined as the noisiness of an octave band of random noise centered at 1000 cps and having a band sound pressure level of 40 dB; "PNdB" was coined as the analog of the phon.

The perceived noise level, then, in PNdB of a given sound is the sound pressure level of the octave band of noise at 1000 cps that is judged to be as noisy or unacceptable as the given sound. Perceived noise level in PNdB was proposed as a more appropriate yardstick for estimating the subjective acceptability or noisiness of complex sounds, aircraft sounds being one example, than is loudness level in phons. The calculation of perceived noisiness of a sound can be accomplished with the use of publicized figures and tables (ref. 43) and the following formulae for a total effective noy value (N):

1. For octave band spectra: $N = n_{max} + 0.3\ (\Sigma n - n_{max})$
2. For 1/3 octave band spectra: $N = n_{max} + 0.15\ (\Sigma n - n_{max})$
3. For 1/10 octave band spectra: $N = n_{max} + 0.07\ (\Sigma n - n_{max})$

where n_{max} is the number of noys in the noisiest band and Σn is the sum of noy values in all the bands. These formulae and the factors .3, .15, and .07 for the full, 1/3, and 1/10 octave band spectra, respectively, represent the functional relations found by Stevens between loudness and the bandwidth of noise.

It further appears that the perceived noise level of sounds not involving intense pure-tone components or other sharp spectral variations can be estimated to some degree with a simple sound level meter plus a weighting network having the shape of the 40-noy equal noisiness contour (ref. 42). A sound level meter with this weighting network, called "N" weighting, is used at several airports in the United States for monitoring the noise level of operating aircraft to determine if, and when, such levels exceed certain limits; the readings can be expressed as dB(N), analogous to dB(A) or dB(C) (refs. 38,41).

Relations between Loudness and Noisiness

The concept of perceived noisiness by Kryter (ref. 39) is not as ambitious as one might wish it to be. Perceived noisiness is what people say their subjective impression is of the unwantedness or unacceptability of a sound. As in the case of loudness judgment, perceived noisiness judgments are nearly always relative, not absolute, judgments: that is, one sound is judged as being equal to, more than, or less than another sound with respect to its unwantedness -- the sounds may both be considered in an absolute sense tolerable or intolerable to the person making the judgment.

Secondly, as with loudness, the equal noisiness contours, showing how perceived noisiness varies as a function of frequency, were determined with narrow bands of random noise that had little or no meaning to the listeners -- obviously, it would be impossible to use sounds having different meanings or emotional effects upon people when deriving equal noisiness contours.

Whether or not loudness as calculated by the Stevens and Zwicker methods, or any other loudness procedure, adequately predicts the loudness of complex sounds, the fact remains that people are generally interested in how unacceptable or unwanted a sound is; and this being the case, we believe tests show that there is a basic attribute of "noisiness" to sounds that is often different from loudness, although there is no question that semantic and experimental difficulties can be a source of confusion to both the subjects and the experimenters in this problem area.

Although it is not usually possible or necessary to "explain" our perceptual abilities, it is perhaps helpful to postulate some possible mechanism or reason why there should be basic attributes to sound other than those of pitch and loudness. In short, why should people be more averse to higher frequencies than to lower frequencies? It is, of course, conceivable that most of the psychologically unpleasant sounds people are exposed to in their life tend to be higher rather than lower in pitch, and hence they learn to associate unpleasantness with high pitchedness. Another possibility is that because the ear is particularly susceptible to auditory fatigue and damage as the result of exposure to sound frequencies in the region of 1500 to 4000 cps or so (the region where the equal noisiness contours deviate the most from the equal loudness contours as shown in figure 12), people learn from experiencing tinnitus (a "ringing" sensation in the ears) and temporary auditory fatigue (as measured by a shift in threshold of audibility) that frequencies in the region from 1500 to 4000 cps are potentially more harmful and are to be more avoided than sounds of lower and possibly higher frequencies.

Noisiness of Combinations of Noise and Pure Tones

We saw in figure 12 that the difference between equal loudness and equal noisiness contours for bands of random noise is significant at higher frequencies but not tremendously large.

However, the difference between loudness and perceived noisiness is unmistakable when subjects judge sounds that consist of pure tones superimposed or immersed in a band of random noise. Scharf (ref. 89), for example, found that the loudness of a subcritical band is independent of the energy distribution within it or the number of its components. On the other hand, as will be shown below, a tone can contribute as much as an effective 10 dB-15 dB to the judged noisiness of a sound over and above the amount to be expected on the basis of either loudness level or perceived noise level as normally calculated.

Method of Wells and Blazier. - Wells and Blazier (ref. 103) have recently proposed a method for computing the subjective reaction to complex sounds that attempts to account for the effect of pure-tone components on judged noisiness. For a given sound spectrum, the initial Wells and Blazier approach assigns one of a family of frequency-weighted contours shown in figures 13 and 14 tangentially closest to the actual spectrum of the sound in question. The contour levels are designated by a single band sound pressure at a specified frequency. However, Wells and Blazier found that this method was as much as 18 dB in error when used to evaluate the judged noisiness of broadband noise or broadband sounds containing pure-tone components. To overcome this deficiency, Wells and Blazier proposed that in using the tangent contour method, a correction be made to the spectra according to its bandwidth. The proposed correction to the value of the tangent contour for the spectrum shape of the noise is shown in figure 15. This correction varies as a function of the number of 1/3 octave bands within 5 dB of the highest contour tangent to the sound spectrum.

For spectra containing a pure tone, a double computation is employed. First, the broadband portion is considered as above. Second, the pure-tone corrections are applied to the original spectra according to the lower curves on figures 13 and 14; the contour tangent to the corrected tone levels is then obtained. Third, 6 dB is subtracted from this level (applying figure 15 for $n = 1$) to obtain the corrected pure-tone contour level. Finally, the composite corrected contour level is obtained by adding the corrected broadband and pure-tone contour levels together on an energy basis.

Proposed single pure-tone "adjustment" procedure for PNdB. - As proposed by Little (ref. 50) and Wells and Blazier, a simple way to " adjust " the measured sound pressure levels, in order to take into account the additional noisiness resulting from the presence of a pure tone, would be to add to the level of the band with the pure tone the decibel difference that exists between the octave band of noise alone and the level of the band plus the pure tone when the two sounds are judged to be equally noisy. The perceived noise level of a complex sound would then be calculated on the basis of the " adjusted " band sound pressure levels.

However, sound spectra of "real-life" sounds would typically be found by filtering with octave band or 1/3 octave band filters the mixture of the broad continuous spectra noise and the more or less steady-state pure-tone components; thus, the effective level of the pure tone without the background noise would usually not be measured. For this reason, it is important to also specify an "adjustment" factor that can be applied to band sound pressure level measurements made of the total complex sound.

Accordingly, in figure 16, Kryter and Pearsons (ref. 44) plotted the adjustment to be added to the sound pressure level of a full, 1/3 or 1/10 octave band of noise containing a pure-tone component as a function of: 1) the tone-to-noise ratio (T/N) when the tone is measured independently of the background noise; and 2) in terms of the tone-plus-noise level relative to the full, 1/3 or 1/10 octave band level of adjacent bands (T+N/AN). In the formula T/N, T stands for the intensity of the tone alone, and N, for the background noise level in the band containing the tone; in the phrase T+N/AN, T+N stands for the intensity of the tone and the background noise in a given band measured when both are present, and AN is the intensity of bands immediately adjacent to the band containing the pure tone. The use of T+N/AN is based on the assumption that the background noise over several bands will be relatively "flat" in level, but that a more or less steady-state pure-tone component is present in one of these bands.

Figure 17 represents an attempt to develop a general set of pure-tone adjustments as a function of frequency. From this figure one can determine the correction factor to be used for a band of any center frequency. The contours shown in figure 17 are drawn on the assumption that the precise position of a pure tone within the measured band of noise is of minor importance. Although these functions were determined from judgments of bands of noise with the pure tone placed only at the center frequencies of the bands, it is believed that a reasonable deviation from the center frequency of the band by the pure tone would not appreciably affect the perceived noisiness of the sound. The narrower the band used for measuring the spectra, of course, the less would be this possible error.

Effects of multiple and modulated pure tones on perceived noisiness. - Pearsons, Woods, and Kryter (ref. 66) recently completed a preliminary study of the effects of multiple and modulated pure tones immersed in a broadband background noise upon perceived noisiness. The results would indicate the following:

1. The amplitude and frequency modulation imposed upon one or more of the pure tones did not increase the subjective noisiness of these sounds relative to the noisiness of the steady-state or unmodulated sounds; and

2. The presence of either modulated or unmodulated pure tones imposed on a broadband background noise did not increase the noisiness of these complex sounds relative to the noisiness of the broadband sound without pure tones. These conclusions are made evident by the fact that the perceived noise level calculated without regard for pure-tone effects better predicts the results of the judgment tests than does the perceived noise level with pure-tone adjustments of figure 16 included.

These findings are obviously in disagreement with the results of the aforementioned experiment with single pure tones as well as the results of studies conducted by Little (ref. 50) and Wells and Blazier (ref. 103) on the noisiness of broadband sounds containing pure-tone components. One reason which may explain this disagreement is associated with the two kinds of judgment tests that have been employed in investigations of noisiness. In the earlier single pure-tone study of Kryter and Pearsons, the method of paired-comparisons was used, whereas in the present investigation the method of individual adjustment was employed. We have found in the past that the method of paired-comparisons apparently forces the subject to make a quick judgment of the overall noisiness of one sound relative to a second sound without giving, which is probably desirable, the subject an opportunity to subjectively "analyze" the basis of his judgment. This is probably partly because the subject has to quickly make his response in a 2- or 3-second interval before he is again presented with a pair of stimuli, and partly because the pairs of stimuli are usually presented in a very "random" sequence where successive pairs of sounds do not bear any relation to each other. This tends to make the subject consider each pair of sounds on their own merit, which is also probably desirable, independently of any similarities or dissimilarities a given pair may have with other pairs.

The important effect the method of judgment can have is illustrated by the results of tests where subjects were asked to equate sounds of different intensities and durations. Here it was found important to use the method of paired-comparisons rather than the method of individual adjustment because when the method of individual adjustment was used, subjects invariably adjusted the comparison sound so that its peak level tended toward the peak level of the standard sound with little regard to differences in duration of the two sounds; on the other hand, when the method of paired-comparison was used, the subjects reacted, apparently, to both the duration and intensity factors.

It is quite possible, then, that when we ask subjects to make subjective judgments of the sort required in the present experiment he may, as he makes repeated judgments, concentrate on some common aspect of the two stimuli he is attempting to judge and will, if it is under his control, make adjustments to one stimulus until it tends to be equal to the other only with respect to this common aspect; in short, this makes his task easier and, to him, more reliable or repeatable.

We would like to suggest, as a tentative hypothesis, that the subjects in this later multi-tone experiment may have either consciously or unconsciously partly ignored the pure tones and made their judgments mainly on the bases of the broadband noise levels. The fact that the results were so consistently predicted regardless of the number or degree of modulation of pure tones when the PNdB's were calculated without pure-tone correction factors would suggest that the subjects might have been making their judgments on that basis.

There are, of course, other possible explanations for the apparent disagreement in the results of these various "pure-tone" experiments. For example, it should be noted that in the single pure-tone studies the tones were embedded in a single octave band of background noise, whereas in the multi-tone investigation the tones were embedded in a broadband noise extending from about 125-6300 cps. It is possible the broadband background was the dominant factor rather than the multiple pure tones in determining the noisiness of the sounds, and that the single octave band of background noise used in the previous study was subdominant to the single pure tone. It is also conceivable that inasmuch as the pure tones were harmonically related they may have been perceived as a "musical" sound and thereby lost any significant noisiness they might otherwise have.

It is clear that further experimentation will be required to answer the questions raised by these experiments. It is perhaps not unreasonable to hypothesize that the overall subjective noisiness of these sounds can be better equated by the method of paired-comparisons than that of individual adjustment, and that judgments obtained from a paired-comparison test would be more highly correlated with the basic response we wish to evaluate -- namely, the subjective reaction of a person responding to such a complex sound in everyday life.

Tentatively recommended procedure for calculation of perceived noise level. - Kryter and Pearsons (ref. 44) recommended that the "3 dB rule" be applied to either full octave, 1/3 octave, or preferably 1/10 octave band spectra when listening reveals the presence of audible pure tones in a complex sound. This "rule" implies that if a band exceeds its adjacent bands by 3 dB, a pure tone is present. Therefore, whenever a band equals or exceeds this 3 dB criterion an adjustment should be added in accordance with the vertical ordinates of figures 16 or 17. Following this adjustment, the perceived noise level of the complex sound would then be computed in accordance with the procedures developed previously for broadband, continuous spectra sounds.

In view of the recent results found with multiple and modulated pure tones, the pure-tone adjustment factor shown in figure 16 and 17 should probably be applied only to sounds containing a predominant, single, pure tone in a background of random noise until further evidence on this matter is available.

Ambiguities in spectral measures. - The suggested "rule" that a pure-tone component is present whenever the overall sound pressure level in a band exceeds its adjacent bands by 3 or more dB is, of course, not infallible. Spectral measurements, particularly when the energy in narrow-band filters is integrated over too brief a period of time, could, on occasion, because of random, temporal variations in level of the noise components, indicate the presence of pure-tone components when none were present. On the other hand, it should be noted that band spectra of complex sounds can be misleading if: a) a pure-tone component happened to fall in the region of the crossover frequencies of adjacent band filters; or b) the pure tones of about equal intensity occurred in two adjacent band filters. In both of these situations the measured sound pressure level could be the same for two adjacent bands and give a measured spectrum that had the appearance of being "flat" over those two adjacent bands when, in reality, a strong, pure-tone component, or components, were present.

These difficulties could be overcome to some extent with the use of relatively long measurement intervals and 1/10 octave band filters. Because these filters would be, usually, less wide than the critical bandwidth of the ear, one could, with validity, apply a pure-tone correction whenever either one or two neighboring 1/10 octave bands exceeded the immediately adjacent 1/10 octave bands by more than 3 dB.

Effects of Duration on Noisiness

In addition to pure-tone correction procedures, Kryter and Pearsons (ref. 42) have published graphs as shown in figure 18 indicating the exchange required between intensity level and duration of a sound in order to keep the perceived noisiness of the sound constant. This relation shows that approximately a 4.5 dB increase in the level of a sound is equivalent in terms of perceived noisiness to a doubling of its duration. The listeners apparently do not respond simply to the "energy" in the sound when judging its noisiness; if they had done so, the curve in figure 18 would have a slope of -3 dB per doubling of time.

Duration is here measured as the time the sound is within 10 dB of its maximum level. As shown in figure 18, the durations investigated varied from about 2 to 12 seconds. Some real-life sounds have a temporal duty cycle of this order of durations; for example, the sound under an aircraft at an altitude of approximately 1000 ft following takeoff will last about 12 to 14 seconds from the time its level starts at 10 dB below its peak level to the time it declines 10 dB from peak level, and the duration of the sound under the aircraft on approach to landing when at an altitude of several hundred feet will typically be of the order of 6-8 seconds.

One of the apparent major differences between the subjective loudness and noisiness of a complex sound is revealed when a person is asked to judge the loudness and noisiness of sounds of different durations. As aforementioned, the loudness of a sound grows as its duration is increased up to about .2 seconds but remains relatively constant as its duration is extended beyond .2 seconds (ref. 50). On the other hand, as shown in figure 18, the perceived noisiness of a sound continues to be a function of duration at least up to 12 seconds and undoubtedly longer. This, of course, seems as it should be -- the longer an unwanted sound is present, the noisier (more unwanted) it should be to people. In all probability some unit of duration will be selected in the future as a reference standard in the temporal domain to which the perceived noisiness of sounds of other durations are compared or adjusted, just as an octave band of random noise at a sound pressure level of 40 dB is the reference standard in the frequency domain.

VALIDATION OF METHODS FOR ESTIMATING LOUDNESS AND NOISINESS

A number of laboratory studies have been conducted in which subjects were asked to equate the loudness or the noisiness of a wide variety of "everyday" sounds or noises relative to the loudness or noisiness of a tone or band of random noise centered at 1000 cps. The degree to which the results of these judgments can be predicted by so-called "objective" methods of measuring the sound or noise is one measure of the validity and usefulness of these object methods.

The objective measures that appear to be the most practical or valid are dB(C), dB(A), phons-Stevens (S), phons-Zwicker (Z), and PNdB.* All of these measures, except the last, purport to evaluate loudness; PNdB is presumed to evaluate the noisiness or unwantedness of a sound. As previously described dB(C) and dB(A) are broadband measures requiring only a sound level meter for their determination, whereas phons and PNdB require octave or 1/3 octave band measurements of a sound for their determination.

It is unfortunate that all the investigations were not made with the same instructions to judge for equal loudness or equal noisiness. However, some investigators prefer to use loudness, even though they wish to obtain ratings of the unwantedness of the sounds in question. It is possible that the subjects sometimes sense the experimenter's aim and make their judgments accordingly. The converse, of course, also can be true; subjects asked to repeatedly make judgments of the "noisiness" or "unacceptability" of complex sounds may decide to judge relative loudness rather than relative unacceptability.

Table 2 shows how far, on the average, the objective measures deviated from the subjective and presumably "true" loudness or perceived noisiness of the sounds tested. The three columns under each of the headings, dB(C), dB(A), phons(S), phons(Z), and PNdB, reveal the following information about the general validity and reliability of these measures:

> Column 1 represents the average difference between the reference sound centered at 1000 cps (an aircraft flyover noise in Table 2b) and the various comparison noises used in each study;
>
> Column 2 gives a measure of the spread of the original data. The measure of the spread reported, called "absolute deviation," is the average of the set of absolute values of the difference between the subjective-objective difference in Column 1. The larger the "absolute deviation" for a given objective method, the less well does that method predict the subjective value of the sounds judged;

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* The methods recently proposed by Munson for calculating loudness and by Wells and Blazier for noisiness may be valid methods but involve rather complex procedures and have not been widely used. For these reasons these two methods were not included in the comparisons and discussions that follow in this report.

Column 3 shows the "absolute deviation" between the average of the average differences (average of Column 1) and the average differences (Column 1). The larger the deviations for a given objective method in Column 3, the less consistency there is with that method of measurement among the studies; whereas the deviations in Column 2 are a measure of the predictiveness of the different objective methods <u>within</u> each study.

Columns 2 and 3 show that, on the average, the rank order of merit from best to worst, of the several objective methods of measurements, is as follows:

1. PNdB
2. phons(S)
3. phons(Z)
4. dB(A)
5. dB(C)

This same ordering is found whether the consistency of the measures within the studies (Column 2) or among the studies (Column 3) is considered. The same ordering (with the exception of phons(Z) which was not calculated) is also found when different types of aircraft are judged to be equally noisy as shown in Table 2b. However, perhaps the most striking feature of the analysis given in Table 2 is how small the average differences are among these 5 measures in their ability to predict the subjective judgments.

The results listed in Table 2 reflect the relations between subjective judgments and the objective measurements when the various sounds are judged to be equal in loudness or noisiness to a reference sound centered at 1000 cps. Cohen and Scherger (ref. 9) evaluated these objective methods by a different procedure; using a method of paired comparisons they had subjects rate the noisiness (objectionableness) of the sounds from trains, automobiles, and aircraft. From these data Cohen and Scherger were able to: 1) scale the subjective noisiness of the sounds studied and, 2) correlate by two different statistical methods the scales ratings with the objective measurements. The correlations they found are presented in Table 3. Cohen and Scherger suggest that only correlations above .90 can be considered significant for their study. Unlike the results presented in Table 2, the ordering of effectiveness of the octave and 1/3 octave band methods is reversed, with phons(Z) being better than phons(S) or PNdB. However, as found in Table 2, the simple sound level meter values dB(A) and dB(C) were the least accurate predictors of the subjective ratings.

Correlations between the subjective ratings and the various objective measurements for motor vehicle noise are shown in figure 19. It should be noted in figure 19 that in these experiments in which the subjects were asked to rate only the sounds from motor vehicles, dB(A) is often as good or better a predictor of judged loudness or noisiness (except when the vehicles were diesel-powered trucks) than phons(Z), phons(S), or PNdB. The ability of dB(A) levels to predict the subjective ratings of motor vehicle noise is perhaps partially due to the homogeneity of the spectrum of the sound. The spectrum of the sound from these vehicles is always predominantly in the frequency region below 500 cps or so.

There were various, in most cases unknown, factors present in some of the studies included in Tables 2 and 3 and figure 19 that make the results presented suggestive rather than definitive. For example, some but not all of the sounds contained strong but unspecified modulated and steady-state pure-tone components; the duration of the various sounds were not always the same; some of the sounds were undoubtedly noisier than others, but in most of the studies the subjects were asked to equate only loudness; in some cases the reference sound centered at 1000 cps was adjusted to be equal to the comparison sounds set at widely different loudness levels, whereas in other studies only the comparison sounds were adjusted in level, etc., etc.

In brief, the results of many if not all of these validation tests contain unknown "errors" or variables, and to deduce the relative merits of the various objective methods of predicting the subjective reaction to sounds, one must also give weight to theoretical, logical, and practical considerations.

On logical grounds, dB(C) and dB(A), being single measures taken over all frequencies, should perform the worst of the objective methods in estimating subjective loudness or noisiness and, in our opinion (except for the frequency weighting used and lack of correction procedures for pure-tone components) phons(Z) should be the best, at least for loudness. On the other hand, their rank order of merit would be reversed on the basis of ease of their determination in practice. We believe that the methods of measurement used in obtaining phons(S) and PNdB represent, from a measurement point of view, a good compromise between phons(Z) and the simple dB(C) or dB(A) measures; the full and particularly the 1/3 octave band measures required for phons(S) and PNdB are detailed enough to expect good results on the basis of auditory theory, and are more practical for engineering purposes than phons(Z).

Finally, it is proposed that it is the subjective noisiness or unwantedness of complex sounds and not their loudness that is of primary interest to those involved in community noise problems. It is for this reason that the frequency weighting and other procedures developed from experiments concerned with judgments of subjective noisiness, rather than the loudness of sounds, should predict with greatest accuracy and for a wider variety of sounds the subjective reaction of people to these sounds in real life.

This conclusion seems particularly justified when it is noted, for example, that the subject will judge certain high-pitched sounds as well as complex sounds with strong pure-tones as being much noisier than they are loud.

GENERAL CONCLUSIONS

1. Zwicker's graphic method of estimating loudness is, from theoretical considerations of the functioning of the auditory system, probably the best of the objective methods for estimating loudness. From a practical standpoint it is perhaps too difficult for general engineering use.

2. The octave and 1/3 octave band objective methods [PNdB, phons(S), and phons(Z)] of calculating the loudness or noisiness of more or less steady-state complex sounds of broadband spectra appear on an average to be about equally effective in their ability to predict the results of subjective judgment tests, although PNdB gives slightly more consistent and presumably valid results.

3. The objective methods that measure one value over all frequencies, dB(C) and dB(A), are usually worse than PNdB, phons(S), and phons(Z) in the prediction of subjective judgments of the loudness and noisiness of most complex steady-state sounds. dB(A), however, is considerably better than dB(C) and for some homogeneous low-pitched sounds, such as those from most motor vehicles, dB(A) may evaluate their relative loudness and noisiness as well as phons(S), phons(Z), or PNdB.

4. The above conclusions are primarily for broad spectra sounds that do not contain intense pure-tone components. It is found that a pure tone embedded in a broad background spectrum makes the composite subjectively noisier or more objectionable than would be predicted by the various objective measures, including PNdB. A tentative method of adjusting PNdB values to take into account this increased noisiness due to the presence of pure tones embedded in a broad background spectrum is proposed. This method of adjustment appears to be valid for sounds containing single pure tones but may not be appropriate for when several modulated pure tones are present.

5. It has been found that increasing the duration of a sound tends to increase its subjective noisiness. PNdB values can be corrected to predict equal subjective noisiness over the range of at least 2 to 12 seconds and for levels at least between 85 to 115 PNdB, by adding 4.5 dB for each doubling of duration to the PNdB value calculated by normal procedures.

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TABLE 1

Center and cut-off frequencies and bandwidth of critical bands. From Zwicker (ref. 112).

Number	Center Frequencies Hz	Cut-off Frequencies Hz	Bandwidth Hz
		20	
1	50	100	80
2	150	200	100
3	250	300	100
4	350	400	100
5	450	510	110
6	570	630	120
7	700	770	140
8	840	920	150
9	1000	1080	160
10	1170	1270	190
11	1370	1480	210
12	1600	1720	240
13	1850	2000	280
14	2150	2320	320
15	2500	2700	380
16	2900	3150	450
17	3400	3700	550
18	4000	4400	700
19	4800	5300	900
20	5800	6400	1100
21	7000	7700	1300
22	8500	9500	1800
23	10500	12000	2500
24	13500	15500	3500

TABLE 2a

Differences between objective measurements (dB(C), dB(A), phons (S), phons (Z), and PNdB) of a band of noise centered at 1000 cps, or a 1000 cps tone, and recordings of various machinery, motor vehicle, auto horns, aircraft, etc., noises when the tone or band of noise was judged to be just as loud (or noisy, according to Kryter and Pearsons) as the recorded noises.

Investigator(s)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
	dB(C)			dB(A)			phons (S)			phons (Z)			PNdB**		
Quietzsch (ref. 74)	-11.2	5.2	2.7	-13.7	3.9	0.9	-1.7	3.3	0.2	+2.9	3.2	0.0	-1.4	3.2	0.5
Rademacher (ref. 75)	-1.8	2.8	6.7	-10.9	2.3	1.9	+3.1	1.2	5.0	+6.8	1.1	3.9	+2.6	1.2	4.5
Niese '57 63 phon (ref. 64)	-3.7	2.1	4.8	-10.5	2.9	2.3	+0.3	1.9	2.2	+5.8	2.1	2.9	-1.6	0.9	0.3
Niese '57 60 phon (ref. 64)	-6.5	2.8	2.0	-11.0	2.0	1.8	-0.6	1.1	1.3	+6.1	1.4	3.2	-2.3	2.0	0.4
Niese '59 80 phon (ref. 64)	-9.5	3.1	1.0	-12.6	3.2	0.2	-2.2	2.3	0.3	+4.5	2.4	1.6	-0.6	3.0	1.3
Niese '60 64 phon (ref. 64)	-9.5	5.4	1.0	-13.5	4.7	0.7	-1.6	1.9	0.3	+2.3	1.4	0.6	-3.7	2.0	1.8
Niese '60 85 phon (ref. 64)	-8.0	3.9	0.5	-11.4	4.9	1.4	-3.0	2.1	1.1	+2.4	1.9	0.5	-1.8	2.3	0.1
Lubcke et al (Berlin) (ref. 52)	-12.8	1.4	4.3	-15.5	1.5	2.7	-3.4*	1.6*	1.5*	+1.8	1.3	1.1	-2.5	1.5	0.6
Lubcke et al (Stuttgart) (ref. 52)	-14.4	2.1	5.9	-16.9	1.6	4.9	-6.4*	1.5*	4.5*	-0.1	1.1	3.0	-5.3	1.6	3.4
Kryter + Pearsons (ref. 42)	-7.4	3.4	1.1	-10.6	1.0	2.2	-3.3*	1.3*	1.4*	-3.8	2.8	6.7	-2.8	1.4	0.9
Average	-8.5	3.2	3.0	-12.8	2.8	1.9	-1.9	1.8	1.8	+2.9	1.9	2.4	-1.9	1.9	1.4

Column 1 - Average difference between subjective and objective values.
Column 2 - "Absolute deviation" of data about average difference (see text).
Column 3 - "Absolute deviation" of average difference values in Column 1 about the average of Column 1.

*Phons (S) were calculated by the Mark VI method (ref. 99). Phons (S) in the other studies were calculated by Mark II (ref. 97).

** PNdB values are based on the equal noisiness contours published by Kryter and Pearsons (refs. 42, 43).

Note: The objective measures for this table were not always provided in the original articles referred to in the table. In those cases the necessary calculations were made on the basis of octave or 1/3 octave band data included in the articles or kindly sent to us by the authors. In some cases, octave band spectra were converted (by subtracting 5 dB) to 1/3 octave band spectra in order to calculate phons (Z).

TABLE 2b

Differences between objective measurements (dB(C), dB(A), phons (S), phons (Z), and PNdB) for the sounds from different types of aircraft when they were judged to be equally noisy.

Investigator(s)	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
	dB(C)			dB(A)			Phons (S)			Phons (Z)			PNdB **		
Kryter (ref. 38)	-11.8	3.6	1.0	-4.4	1.7	0.4	-5.1	1.9	0.4	(not calculated)			-4.3	1.7	1.0
Copeland et al (ref. 10)	-7.4	2.6	3.4	-5.0	3.7	0.2	-3.8	2.0	0.9	"	"		-2.7	1.4	0.6
Kryter + Pearsons (Unpublished)	-12.9	2.2	2.1	-6.6	1.9	1.8	-4.5*	1.9*	0.2*	"	"		-3.5	0.6	0.2
Kryter + Pearsons (ref. 41)	-11.0	2.0	0.2	-3.2	2.0	1.6	-5.5*	2.0*	0.8*	"	"		-2.7	1.4	0.6
Average	-10.8	2.6	1.7	-4.8	2.3	1.0	-4.7	2.0	0.6	"	"		-3.3	1.3	0.6

Column 1 - Average difference between subjective and objective values.
Column 2 - "Absolute deviation" of data about average difference (see text).
Column 3 - "Absolute deviation" of average difference values in Column 1 about the average of Column 1.

*Phons (S) were calculated by the Mark VI method (ref. 99). Phons (S) in the other studies were calculated by Mark II (ref. 97).

** PNdB values are based on the equal noisiness contours published by Kryter and Pearsons (refs. 42, 43).

Note: The objective measures for this table were not always provided in the original articles referred to in the table. In those cases the necessary calculations were made on the basis of octave or 1/3 octave band data included in the articles or kindly sent to us by the authors. In some cases, octave band spectra were converted (by subtracting 5 dB) to 1/3 octave band spectra in order to calculate phons (Z).

TABLE 3

Coefficients of correlation between objective physical measurements and subjective ratings of the sound from various vehicles. From Cohen and Scherger (ref. 9).

	Pearson Product Moment Coefficient (r)	Spearman Rank Order Coefficient (rho)
phons (Z)	.96	.98
phons (S)	.91	.92
PNdB	.90	.92
dB(A)	.83	.72
dB(C)	.75	.68

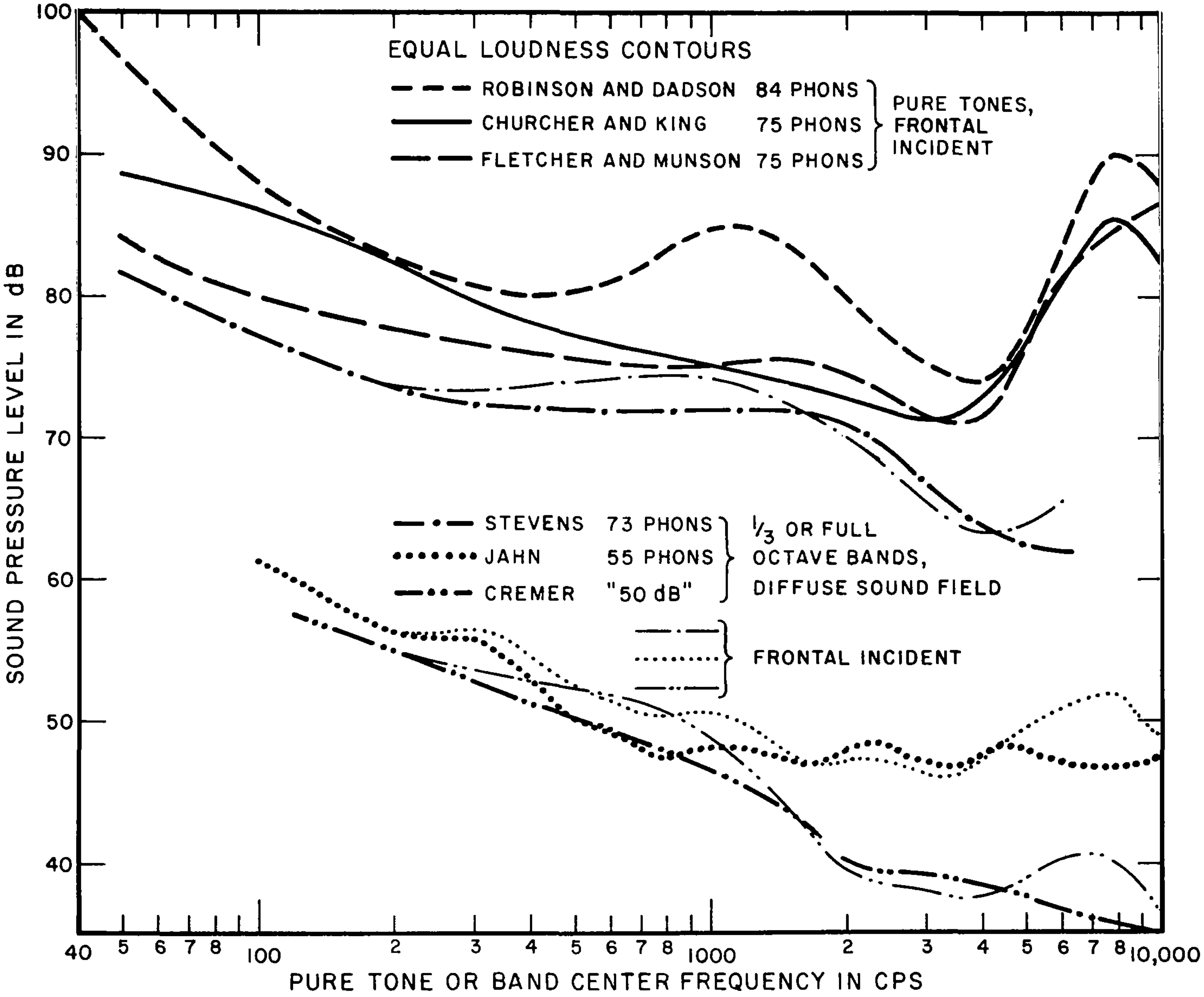


FIG. 1 COMPARISON OF EQUAL LOUDNESS CONTOURS FOR PURE TONES AND BANDS OF NOISE (From ref. 8, 11, 18, 36, 81, 95)

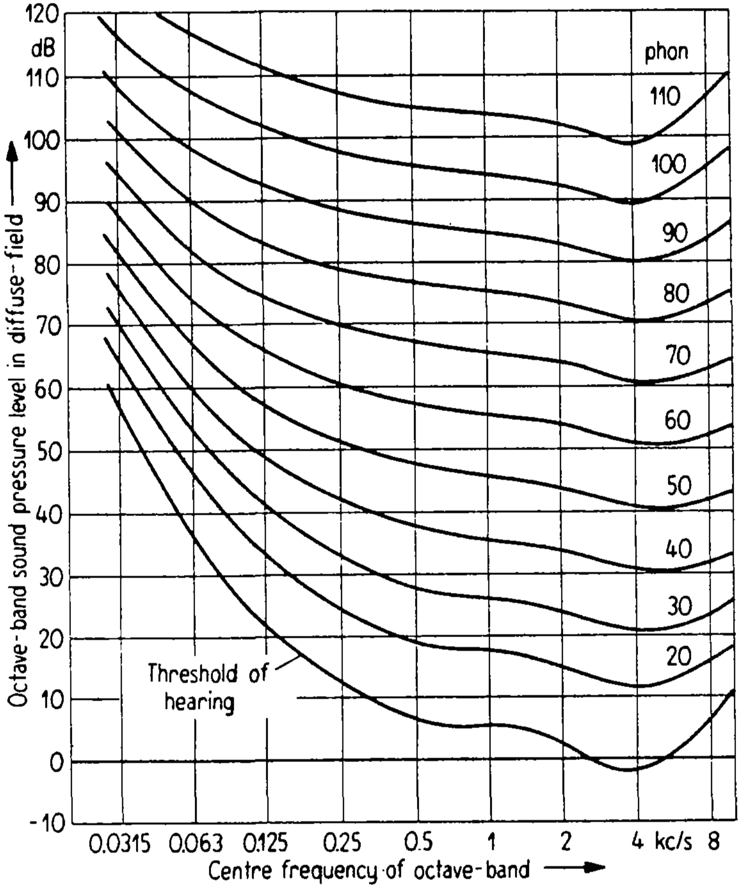


FIG. 2 SMOOTHED DIFFUSE FIELD EQUAL LOUDNESS CONTOURS FOR OCTAVE BANDS OF NOISE.

(From Robinson and Whittle, ref. 87, Crown copyright reserved)

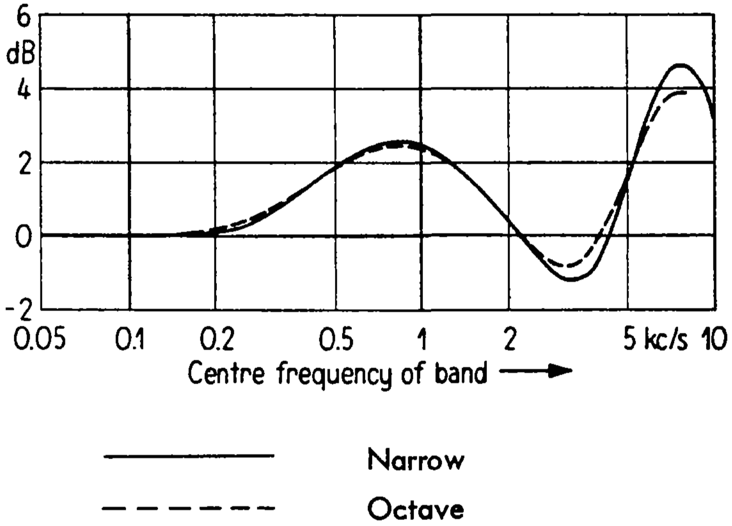


FIG. 3 DIFFERENCE BETWEEN SOUND PRESSURE LEVELS OF FRONTALLY-INCIDENT AND DIFFUSE SOUND FIELDS AT EQUAL LOUDNESS.

(From Robinson and Whittle, ref. 87, Crown copyright reserved)

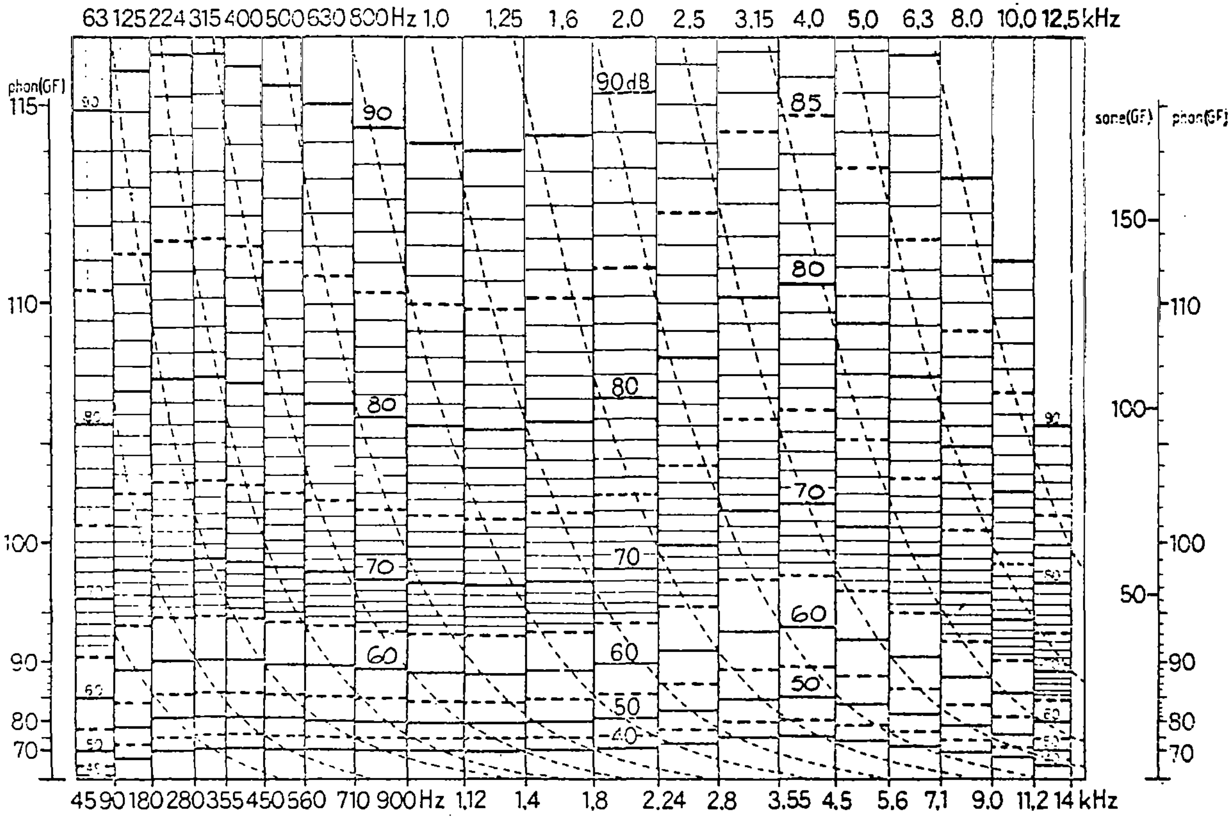


FIGURE 4. LOUDNESS COMPUTATION GRAPH
(From Zwicker, ref. 109)

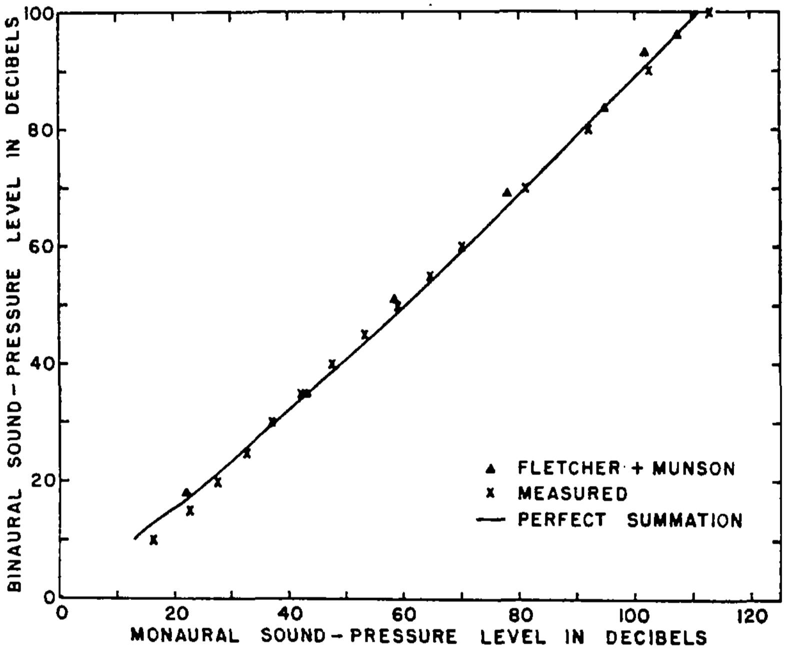


FIG. 5 BINAURAL SOUND-PRESSURE LEVEL AS A FUNCTION OF MONAURAL SOUND-PRESSURE LEVEL AT EQUAL LOUDNESS.

(From Hellman and Zwislocki, ref. 32)

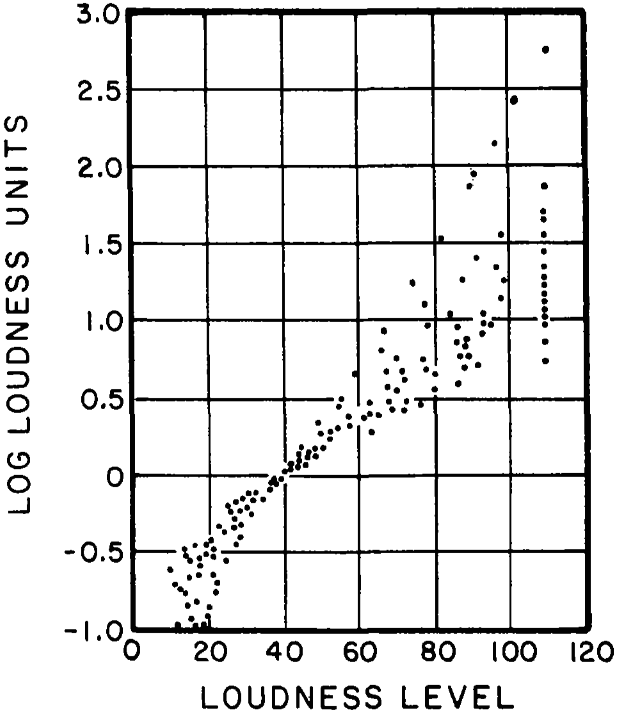


FIG. 6 RESULTS FROM LOUDNESS TESTS WITH 18 OBSERVERS BASED ON FRACTIONATION DATA

(From Garner, ref. 24)

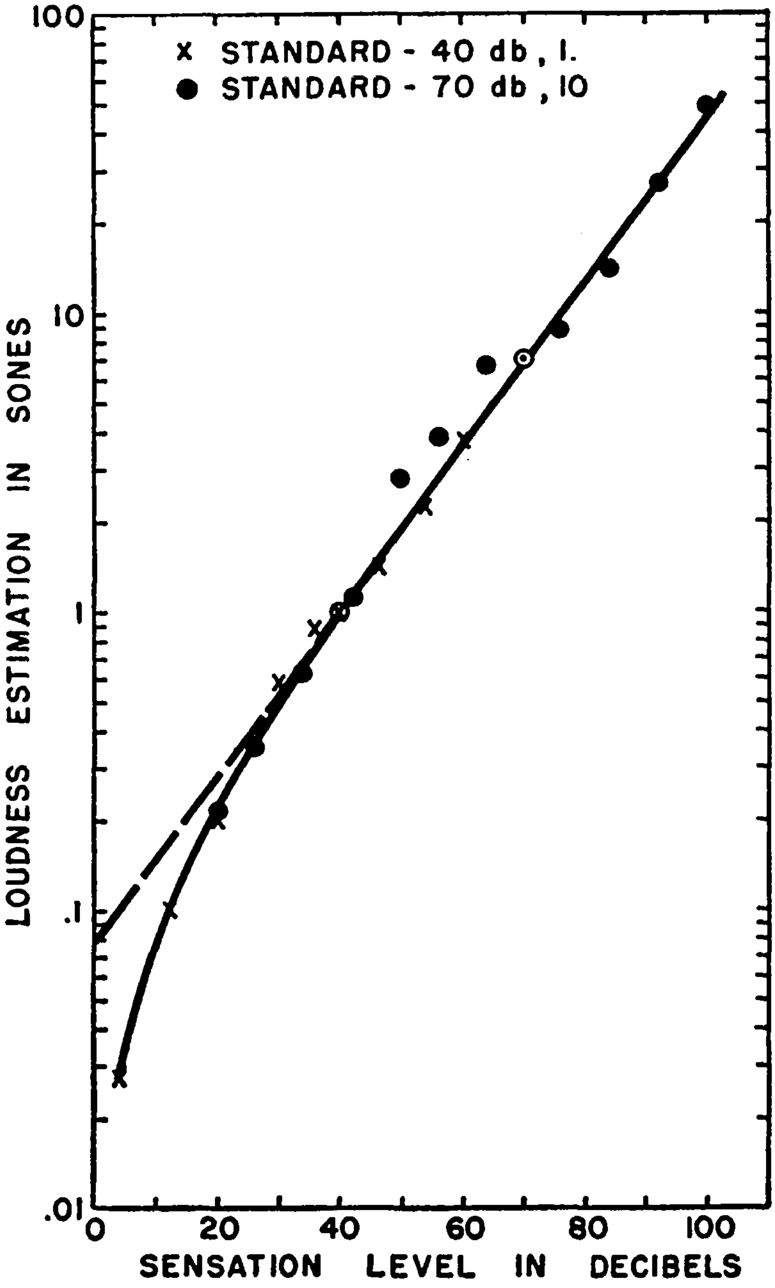


FIG. 7 MEDIAN LOUDNESS ESTIMATES FOR TWO REFERENCE STANDARDS NORMALIZED TO THE 40 dB REFERENCE STANDARD
(From Hellman and Zwislocki, ref. 31)

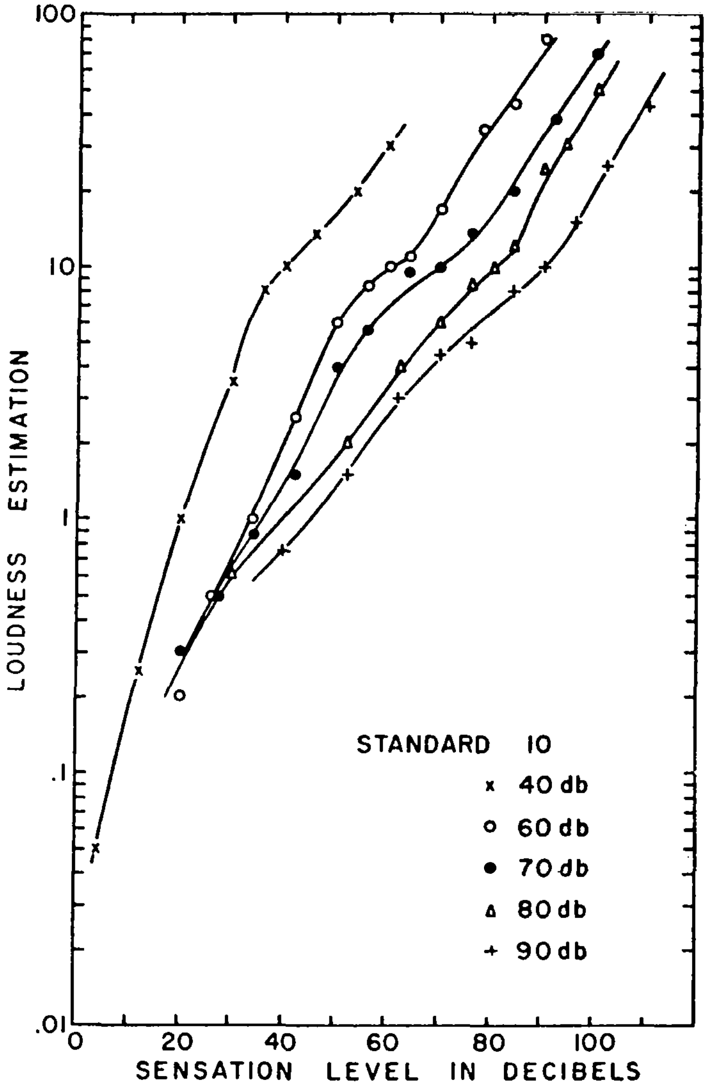


FIG. 8 MEDIAN LOUDNESS ESTIMATES AS A FUNCTION OF SENSATION LEVEL (SL) OBTAINED WITH A REFERENCE NUMBER 10 ASSIGNED TO GIVE REFERENCE SL'S.
(From Hellman and Zwislocki, ref. 31)

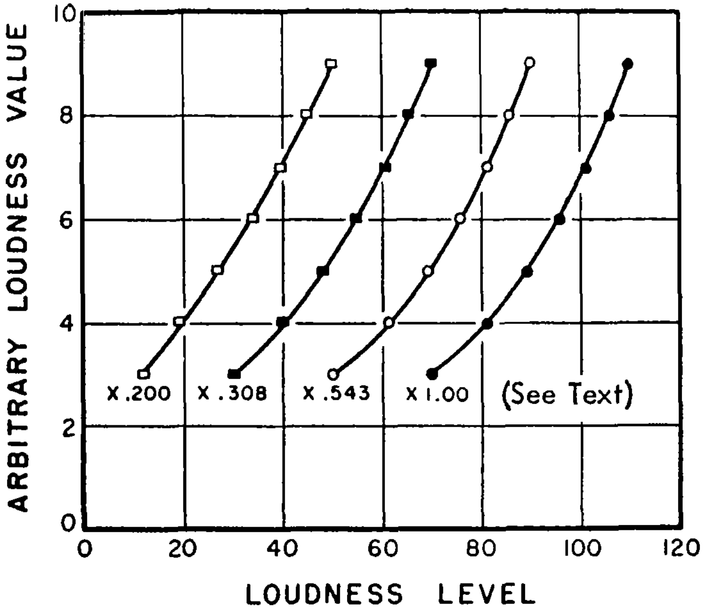


FIG. 9 AN ILLUSTRATIVE SET OF DATA OBTAINED FROM AN EQUISECTION PROCEDURE FOR LOUDNESS JUDGMENTS.
(From Garner, ref. 24)

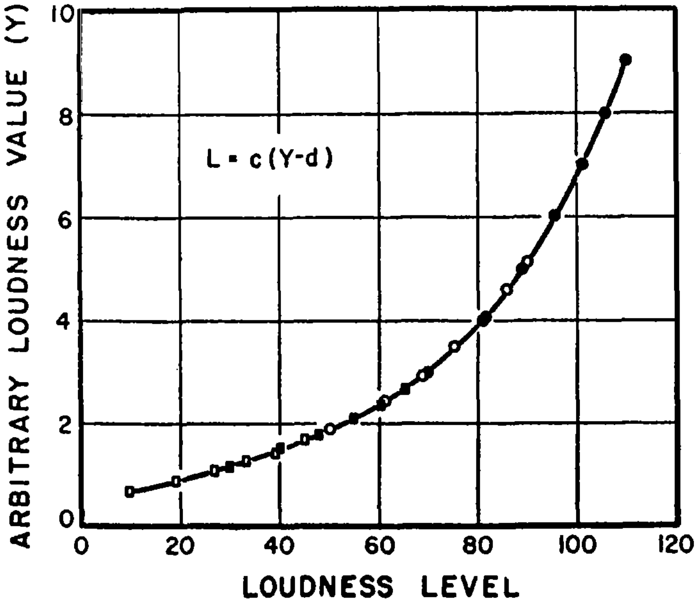


FIG. 10 AN ILLUSTRATIVE LOUDNESS FUNCTION CONSTRUCTED FROM THE DATA OF FIG. 9.
(From Garner, ref. 24)

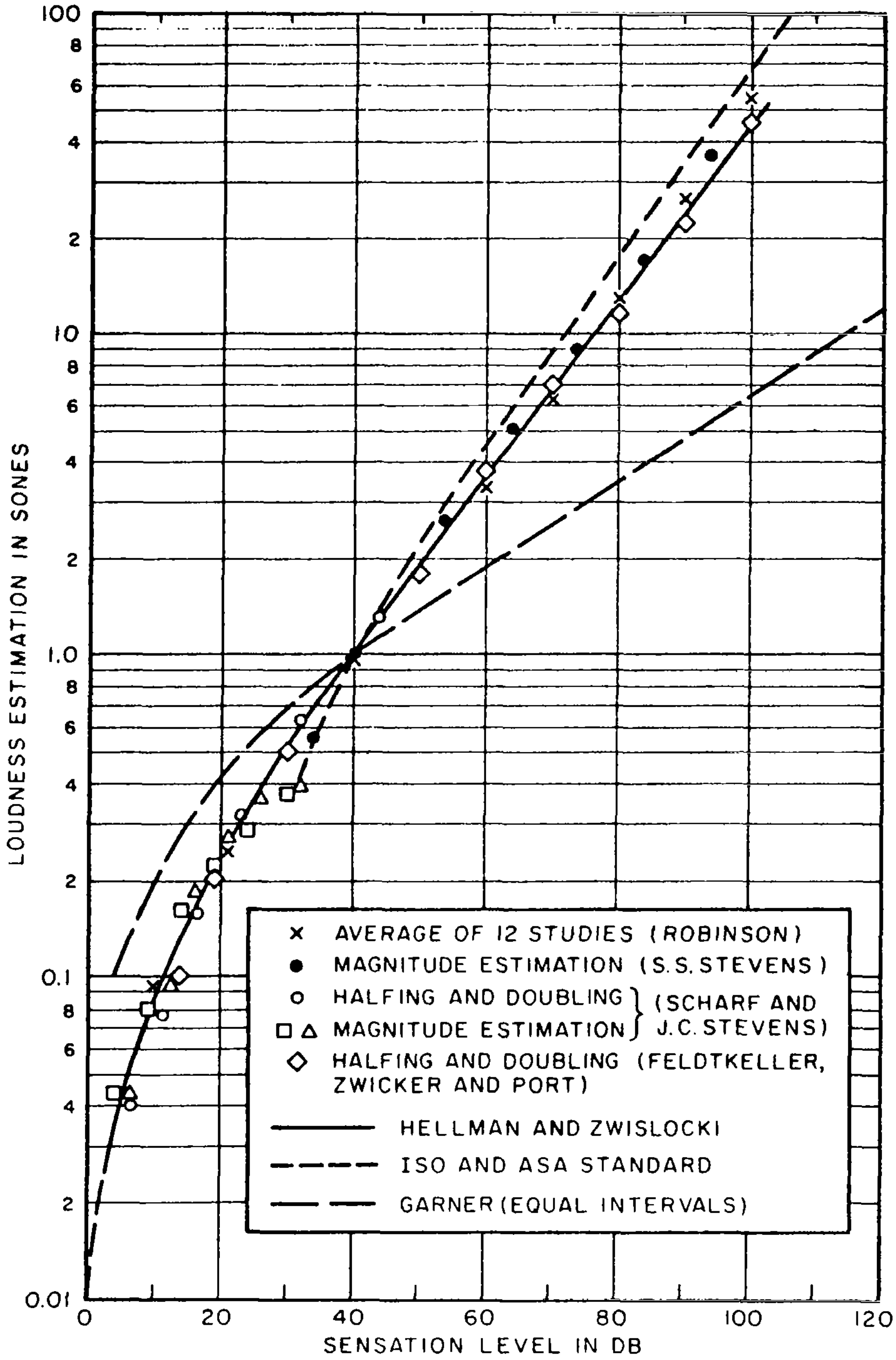


FIG. 11 COMPARISON OF BINAURAL LOUDNESS RESULTS OF SEVERAL INVESTIGATORS

(From Hellman and Zwislocki, ref. 32)

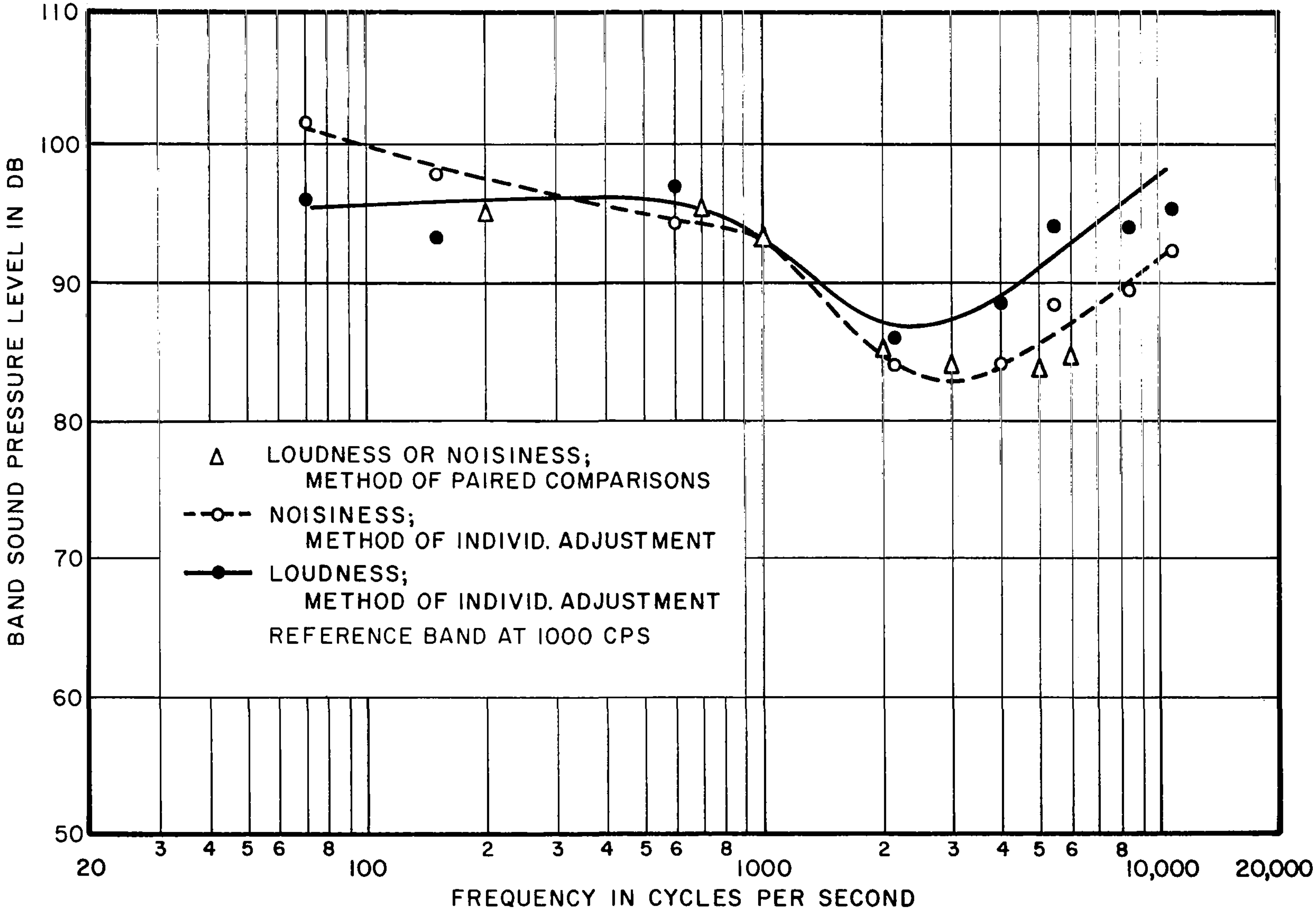


FIG. 12 EQUAL LOUDNESS AND EQUAL NOISINESS JUDGMENTS.
(From Kryter and Pearsons, ref. 42)

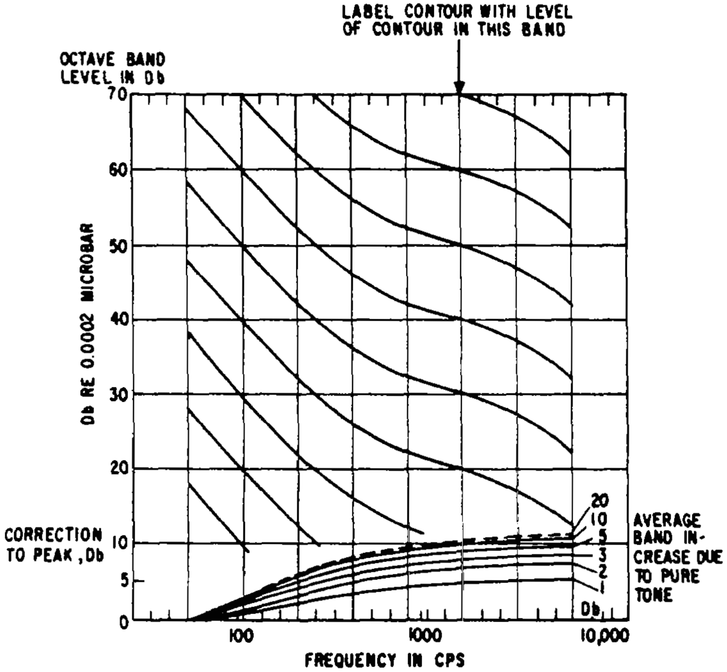


FIG. 13 EQUAL ANNOYANCE CONTOURS AND PURE-TONE CORRECTION CURVES FOR OCTAVE BANDS.
(From Wells and Blazier, ref. 103)

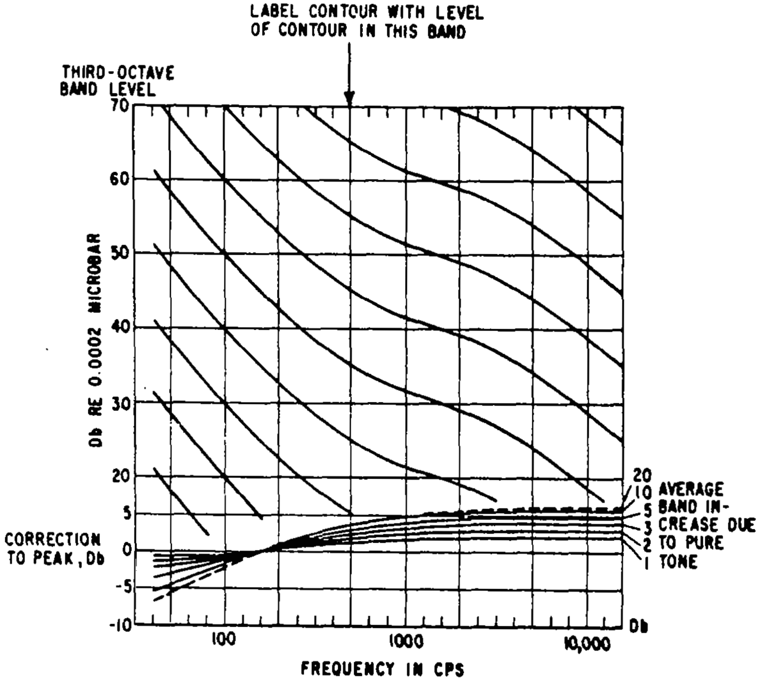


FIG. 14 EQUAL ANNOYANCE CONTOURS AND PURE-TONE CORRECTION CURVES FOR 1/3 OCTAVE BANDS.
(From Wells and Blazier, ref. 103)

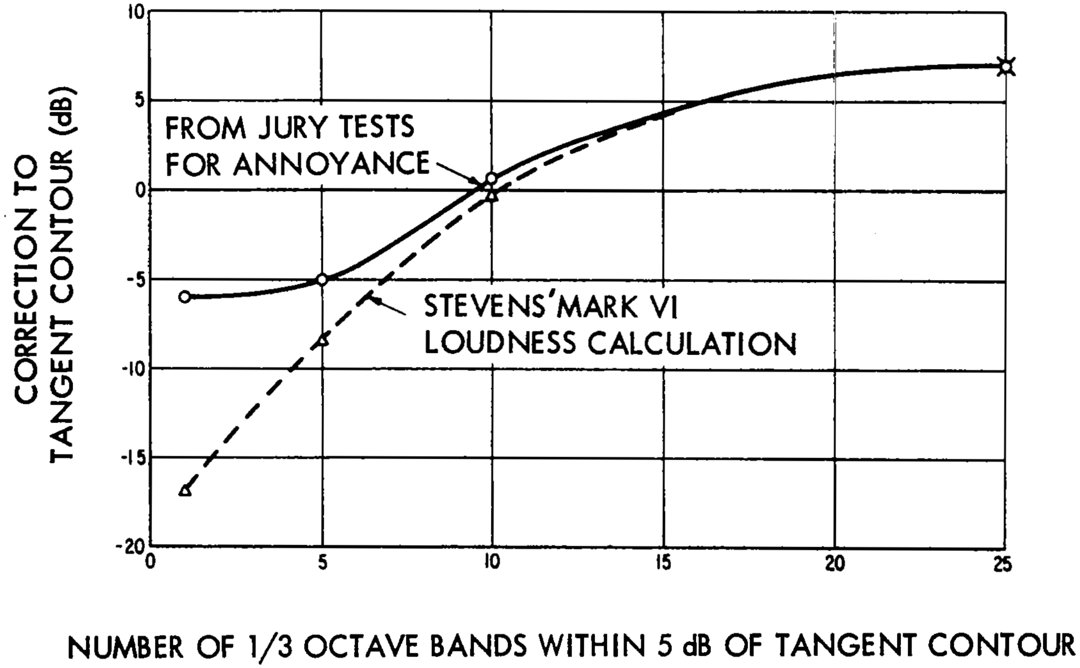
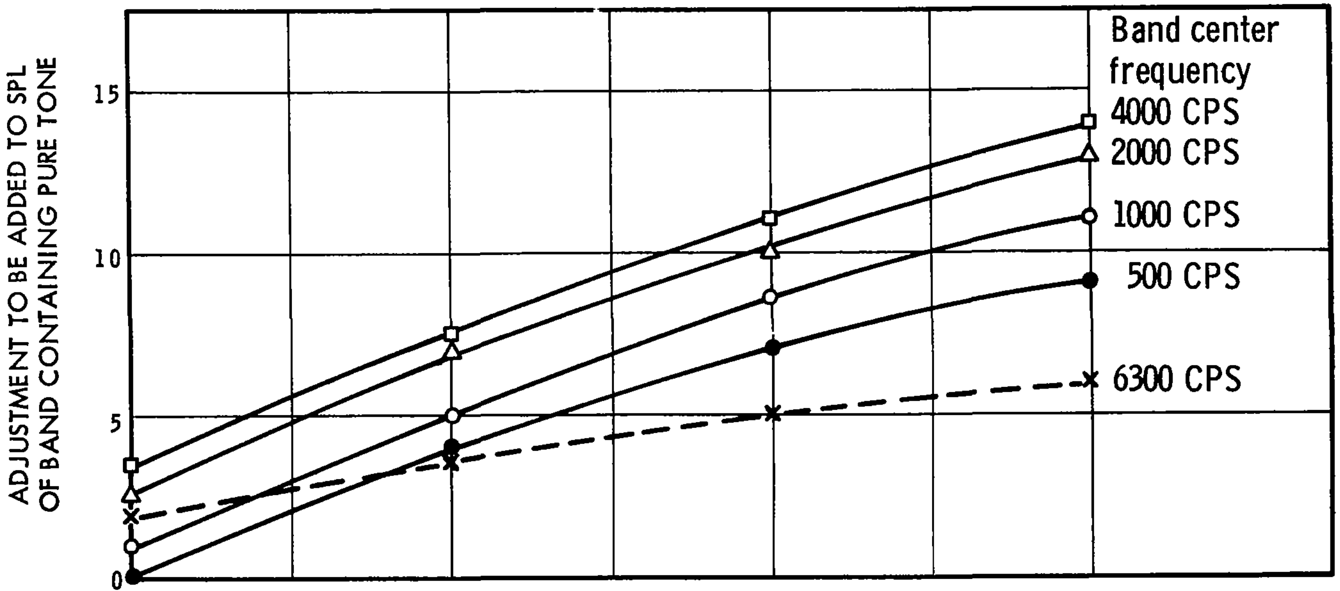


FIG. 15 CORRECTION FOR EFFECT OF SPECTRUM SHAPE ON ANNOYANCE.
(From Wells and Blazier, ref. 103)

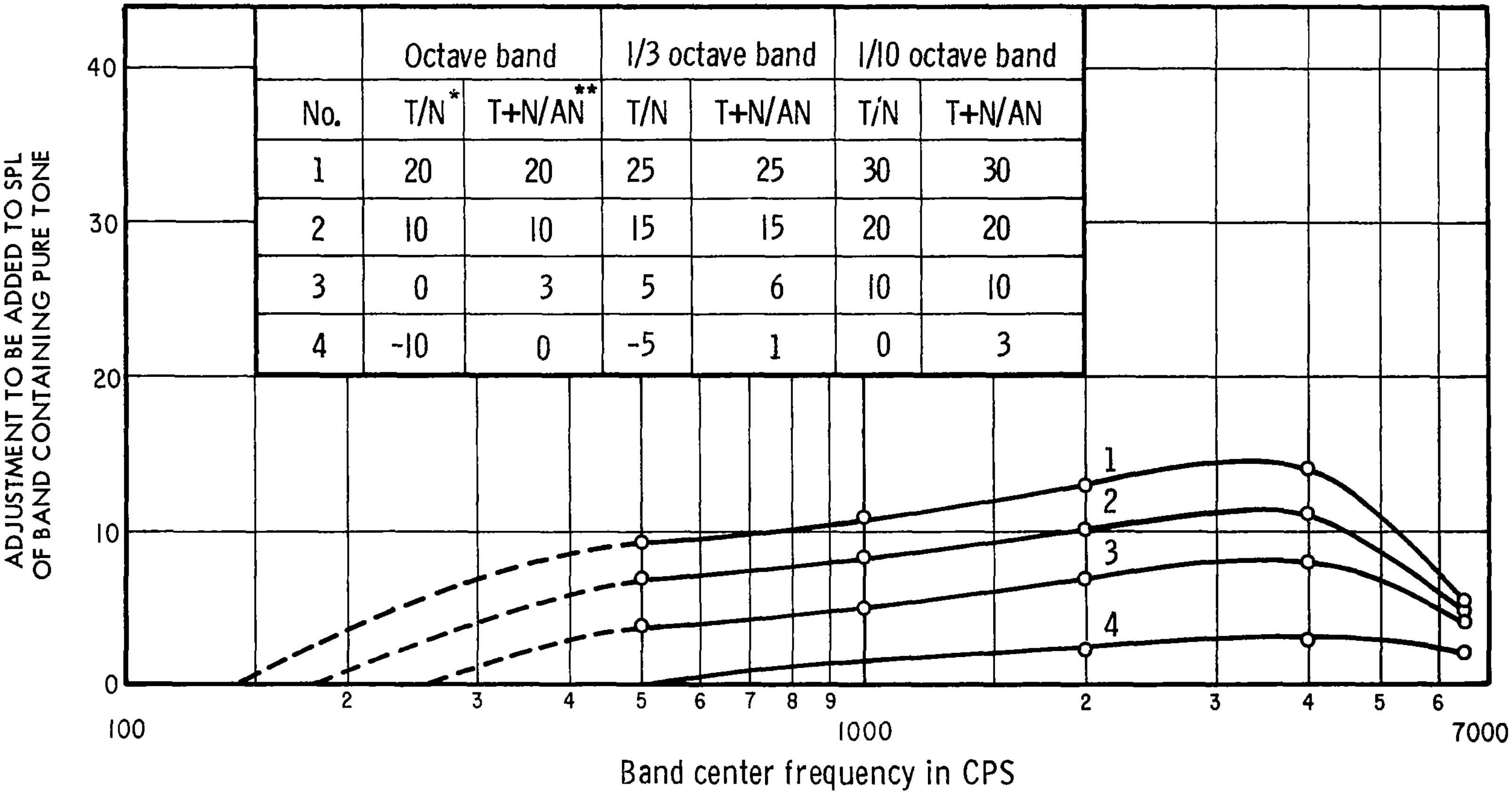


A. Octave band	T/N *	-10	-5	0	5	10	15	20 dB
	T+N/AN **	0	1	3	6	10	15	20 dB
B. 1/3 octave band	T/N	-5	0	5	10	15	20	25 dB
	T+N/AN	1	3	6	10	15	20	25 dB
C. 1/10 octave band	T/N	0	5	10	15	20	25	30 dB
	T+N/AN	3	6	10	15	20	25	30 dB

* Ratio between level of tone and noise measured separately within a band.

** Ratio between level of band with tone and noise together and level of adjacent bands.

FIG. 16 ADJUSTMENT TO BE ADDED TO SPL OF BAND CONTAINING PURE-TONE COMPONENT PRIOR TO CALCULATION OF PERCEIVED NOISE LEVEL.
(From Kryter and Pearsons, ref. 44)



No.	Octave band T/N*	Octave band T+N/AN**	1/3 octave band T/N	1/3 octave band T+N/AN	1/10 octave band T/N	1/10 octave band T+N/AN
1	20	20	25	25	30	30
2	10	10	15	15	20	20
3	0	3	5	6	10	10
4	-10	0	-5	1	0	3

* Ratio between level of tone and noise measured separately within a band.

** Ratio between level of band with tone and noise together and level of adjacent bands.

FIG. 17 ADJUSTMENT TO BE ADDED TO SPL OF BAND CONTAINING PURE-TONE COMPONENT PRIOR TO CALCULATION OF PERCEIVED NOISE LEVEL.

(From Kryter and Pearsons, ref. 44)

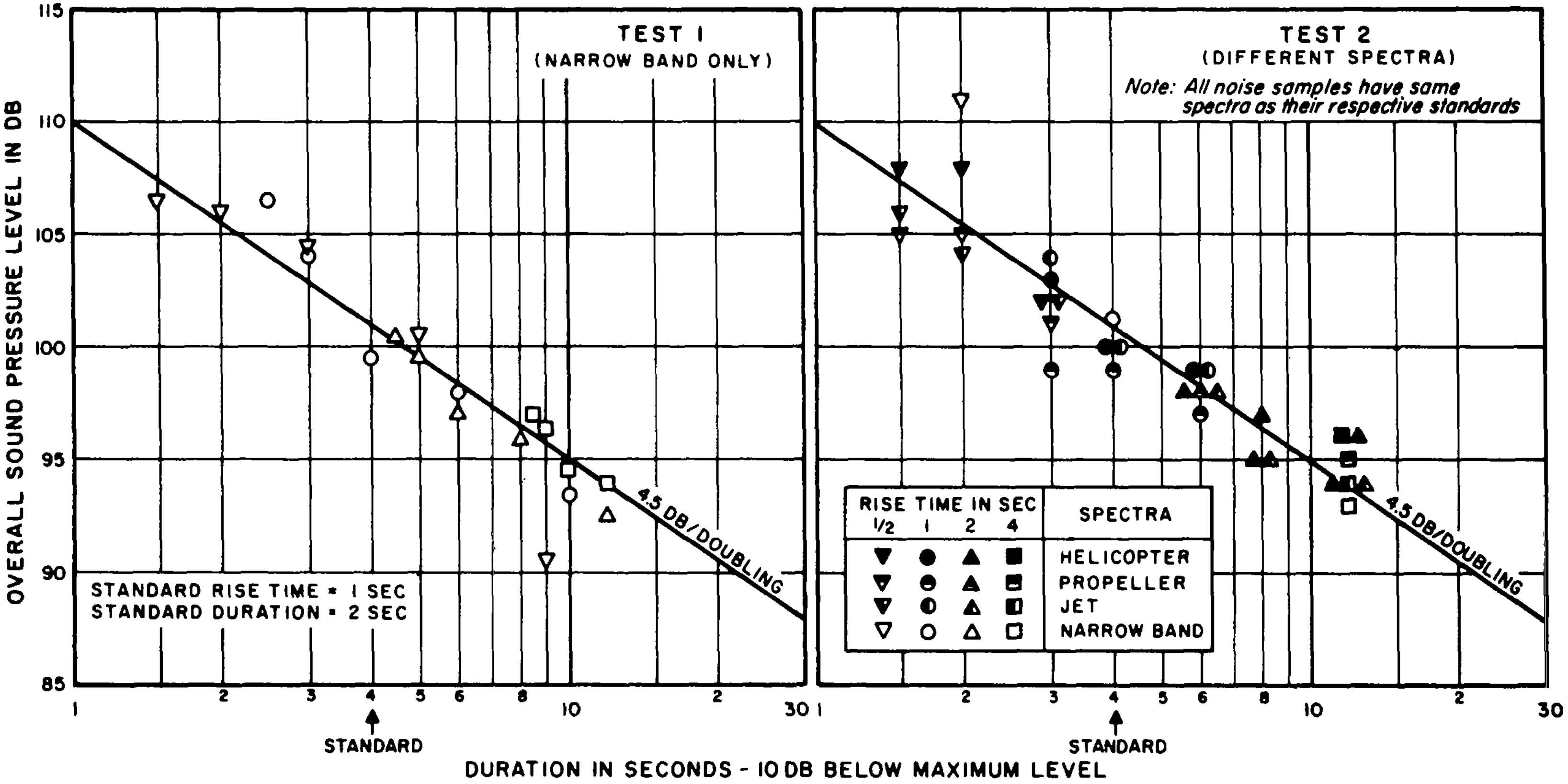
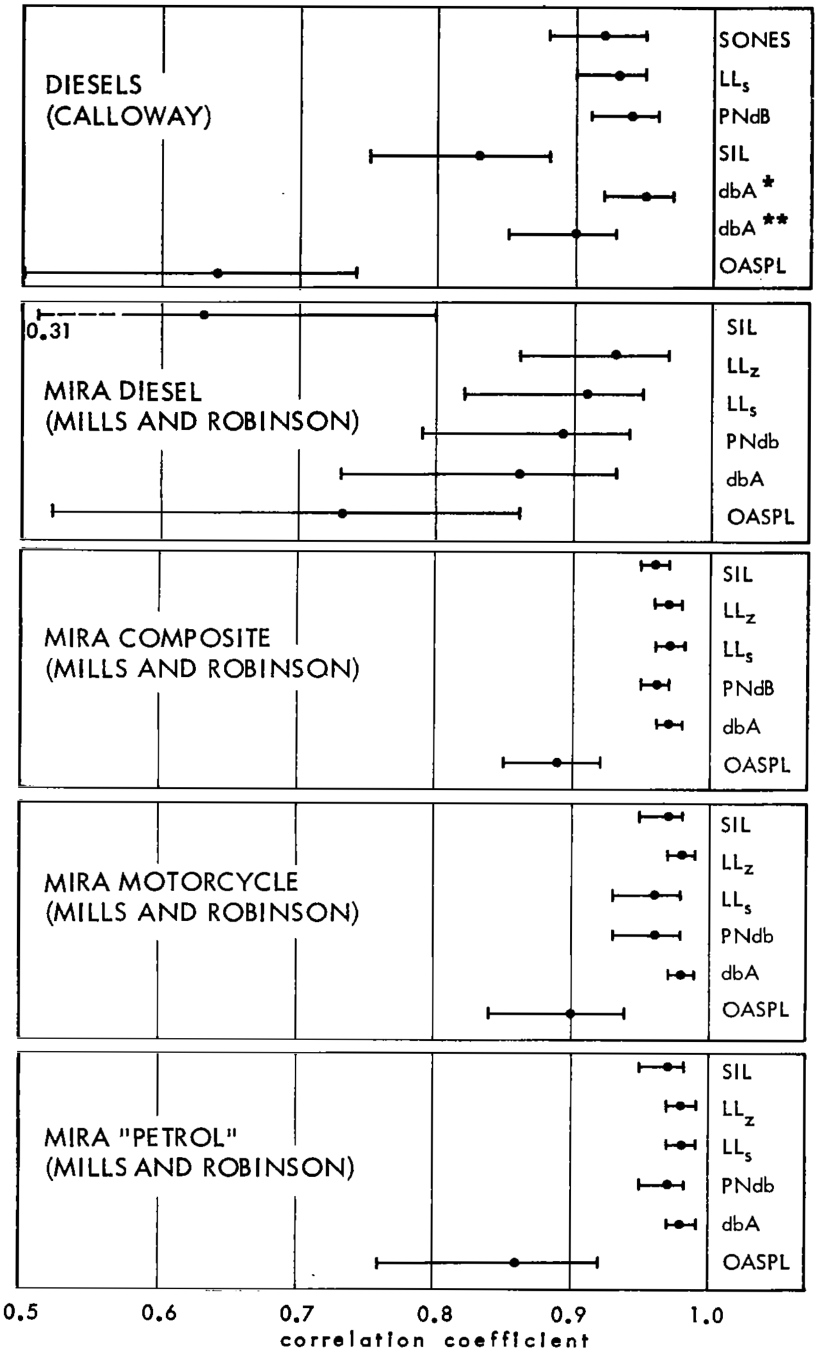


FIG. 18 EQUALLY ACCEPTABLE NOISES OF VARIOUS RISE TIMES AND DURATIONS.
(From Kryter and Pearsons, ref. 42)



* Calculated from octave band measurements.
** Measured on A-Scale

FIG. 19 CORRELATION COEFFICIENTS AND 2S CONFIDENCE INTERVALS FOR VARIOUS MEASURES OF SUBJECTIVE REACTION TO VEHICLE NOISE

(From ref. 4)

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