AMPLITUDE AND LOUDNESS: A SCALING PROBLEM

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The article discusses the relationship of the decibel scale to good scaling procedures. It points out the initial utility of such a scale for problems such as power loss in transmission lines. However, the point is made that when the decibel is used for purposes related to such variables as hearing loss and annoyance the scale properties of the decibel change due to the nature of the underlying variable. Certain problems exist when the decibel is used without taking into account the nature of these changes. Some implications of the power law relationship between sound and psychophysiological variables are discussed.

Stevens (1951) defined four types of scales: nominal, ordinal, interval and ratio scale. Although in many ways the delineation between these scales is arbitrary, he was making a rather valid point. A nominal scale is a scale which distinguishes members of a dimension but does not order them. An ordinal scale is one in which the scale orders the members of the underlying dimension but the distance between the members of the dimension can not be ascertained by the scale. The interval scale is one in which the underlying dimension is represented by a scale such that the distance between the points on the underlying dimension is delineated by the scale, but in which ratios between scale values bear no relationship to ratios in the underlying dimension. The ratio scale is a scale which bears a correspondence to the underlying dimension which is both interval and which all normal mathematical operations can be performed upon the scale while maintaining a one-to-one relationship with the underlying dimension. Dunn (1967) pointed out that the operational definition of the underlying dimension was important in determining what type of operations may be performed on a scale. Thus the scale is not any of the above scales independent of the considerations leading to the definition of the underlying variable. In the case of sound, the decibel scale is a ratio scale as power and intensity ratios are used. Also equal decibel steps tend to be thought of as equal interval steps on an underlying dimension involving the strength or amount of sound (from now on to be called amplitude). In most experiments in psychology and many

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** University of Calgary Acoustics Group in physics where the experimenter presents stimuli at several amplitude levels presumably in equal interval steps, equality of intervals is almost always defined by equal decibel steps. Clearly, these are not equal interval steps if one were considering either pure power or intensity, rather than log power or log intensity, as the scale most directly related to amplitude. There is nothing absolute about either of these measures. There is nothing necessarily wrong with treating equal decibel intervals as equal amplitude intervals. However, if this is done simply as a matter of tradition rather than with a consideration of the objectives defined by the situation, it is a procedure that leads to confusion and misconception about the underlying dimensions being studied.

TRANSFER UNIT

The history of the development of the current units of measurement of amplitude is marked by a very important step in 1924. In that year, the International Advisory Committee on Long Distance Telephoning in Europe was established (Martin, 1929). Part of the purpose of this committee was to propose a universally standardized unit for telephone transmission work. This meeting was also attended by representatives of the Bell System. At this meeting, two power ratios were established, the Neper based upon neperian logs and the Bell based upon the power ratio of 10^1. Here is an example of a decision about units which was primarily pragmatic. This unit was extremely useful for the measurement of power loss in transmission lines (Martin, 1924). It had the distinct advantage that it was independent of frequency and parameters of standard cables (the cable mile was the unit previously used by the Bell System). Martin (1924) also points out that the unit was useful in that it described the hearing function of the human ear. This usefulness was based upon an assumption of the validity of the well-known Fechner Law (Boring, 1942). This law, of course, asserts a logarithmic relationship between sensation and the intensity of a stimulus. Again this assumption about Fechner's Law further added to the pragmatic nature of the decision that was made. Clearly, the new unit appeared to have properties of a ratio scale with respect to two useful dimensions of sound. In fact, the reference value of the decibel scale was chosen to be close to the human threshold for 1000 Hz.

Clearly, the unit which became the decibel was a highly successful unit of measurement. A vast majority of the concerns of people in acoustics were those of electronics, sound transmission, and perhaps architecture. In many respects the size of the Bell System probably guaranteed the transmission concerns would dominate acoustic concerns, at least in North America. The concern with loudness was somewhat later than the concern with transmission. As late as 1929, Watson (1929) was just suggesting that loudness units perceived by the ear should be considered when dealing with the decay of sound in a room. He stated that until that time, decay was always measured in intensity units.

HEARING LOSS

Since that time, the development of acoustics applied to the human organism has proceeded rapidly. The study of the human ear and its relationship to hearing loss was one of the more important of these developments. As more was known about the nature of the ear, and the nature of hearing, it became evident that there were primarily two varieties of peripheral deafness: conductive deafness and nerve deafness. In the case of conductive deafness, the auditory impulse suffers a transmission loss in the outer and middle ear prior to reaching the hair cells. Since in pure conductive deafness, there is nothing wrong with the hair cells, the hearing loss is determined totally by the transmission loss in the outer and middle ear. Thus, hearing loss should follow the rules of a power ratio as does transmission loss. This implies that if a person's threshold is raised by 20 dB, the loudness of the tone 80 dB above his threshold (that is 100 dB) should appear as loud as a tone 80 dB above the threshold (that is 80 dB) of a person with normal hearing. Fig. 1 illustrates this. This indeed is true up to sound pressure levels of near 130 dB (Newby, 1964). The reason for the 130 dB catch-up is probably due to the phenomenon demonstrated by the micro-electro work of Howes (1974) which showed that at near 120 dB the auditory neurons of a squirrel monkey are firing at approximately maximum capacity.

Nerve deafness presents a very different picture. A phenomena usually known as recruitment occurs in the pure nerve deafness case. Recruitment means that if a person's threshold is raised, for instance, by 20 dB, then a tone 40 dB above his threshold (that is 60 dB) may sound just as loud as a tone 60 dB above the threshold (that is 60 dB) of a person's normal hearing. That is, the loudness function of the person with nerve deafness catches up to the loudness function of the person with normal hearing. Since the effect on hearing by white noise masking comes very close to duplicating that of nerve deafness (Hellman & Zwislocki, 1964), the phenomena has been most definitively studied by the technique of using a white noise masker in one ear and no masker in the other ear and having subjects match the two ears for loudness (Fig. 1 is an example of the kind of results obtained). All studies show essentially similar results (Scharf & Stevens, 1959; Lockner & Berger, 1961; Gleiss & Zwicker, 1964; Hellman & Zwislocki, 1964).

A number of people have tried to describe the effect of recruitment in neurological terms. However, a much more parsimonious explanation lies in the nature of the transfer function of the inner ear. This, of course, is a neural transfer function. If one looks at the data of Howes (1974) in which microelectrodes were placed in the neurons of the auditory nerve of a squirrel monkey, one can see that the transfer function is certainly not logarithmic. In fact, it is close through most of the hearing range to a power function with sensation being related to intensity raised to some power less than one. This, of course, is Stevens' well-known Power Law. Although it differs with Fechner's Law, it is

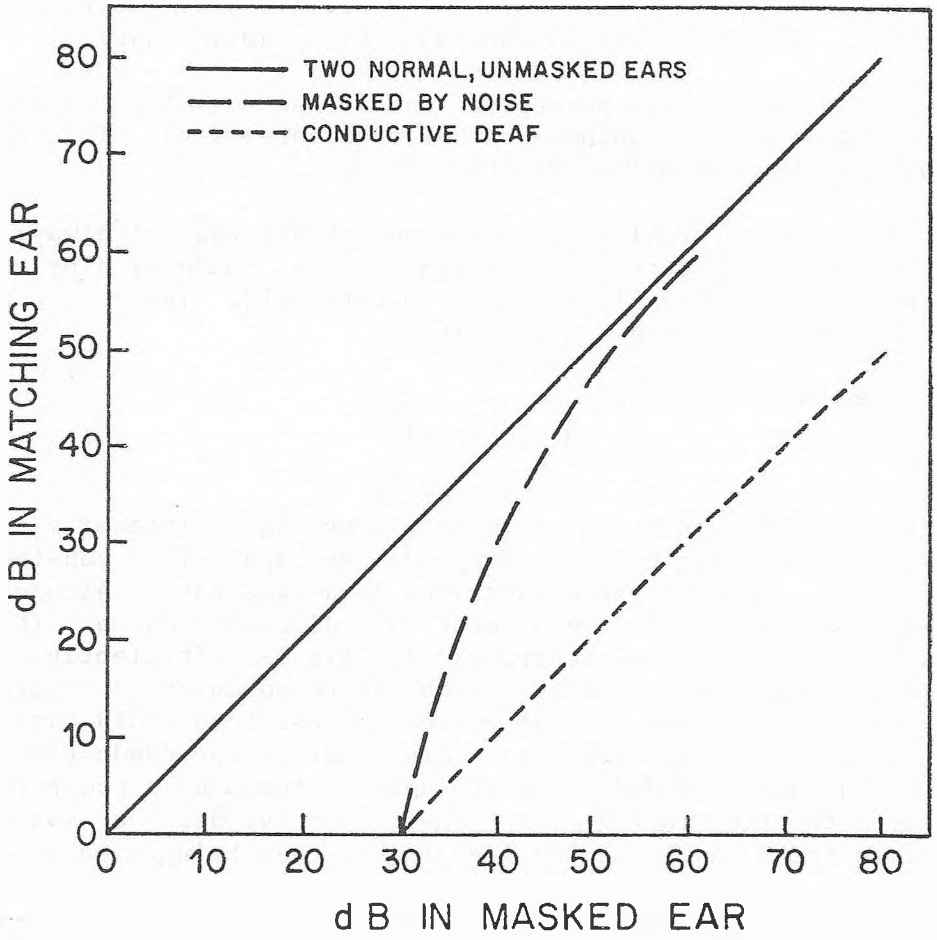

Fig. 1. Including anticipated results from three matching experiments. In all experiments a tone in the "masked ear" is matched in loudness in the other ear by a subject manipulating an attenuator. The solid line represents the case where both ears are unmasked and normal. The long dashes represent the case where the "masked ear" is truly masked by noise. The short dashes represent a case where the "masked ear" is "masked" by the faulty conductive mechanism in the outer or middle ear.

derivable from the Weber fraction (Boring, 1942):

$$\Delta I/I = K \qquad (1)$$

where ΔI is the difference threshold for hearing at intensity I, and K is a constant. The Power Law is derivable by assuming that:

$$\Delta S/S = K \qquad (2)$$

where ΔS is the size of the perceptual unit at sensory level S (sensory level implying perceived loudness rather than intensity). This implies that ΔS varies with intensity (Stevens, 1960).

One of the major problems with Stevens' Power Law has always been that the line which is straight on a log-log plot suddenly dips towards the abscissa at intensity levels close to threshold. This has caused the standard equation which can be written:

$$S = KI^n \qquad (3)$$

to be modified variously to:

$$S = K(I-I_o)^n \qquad (4)$$

or:

$$S = K(I^n-I_o{}^n) \qquad (5)$$

where S again equals sensation, I is intensity, I_o is intensity at threshold, where n is an empirically derived exponent and K is a constant of proportionality. Both of these functions do a reasonable, although not perfect, job of fitting the recruitment data discussed above. (Howes' 1974 data shows why this may be true.) The fit is sufficiently good that it is certainly not any more reasonable to postulate a separate law for recruitment in the case of nerve deafness than would have been to postulate special laws for negative recruitment in the conductive case had the initial unit decided on by the Bell System been a power function. In that case, the line in Fig. 1 for the conductive deaf ear would have diverged from the normal-unmasked line rather than being parallel to it. Would a special concept for that phenomenon have come to exist? Probably. What value would such a concept have had? Clearly, it would have been in defiance to any attempt at parsimony. Incidentally in Menieve's disease a type of recruitment that is in no way artifactual exists.

One implication of all of this is that although a hearing aid which amplifies on a logarithmic basis is ideal for conductive deafness, a hearing aid which amplifies a power-law basis is ideal for pure nerve deafness. It is true that the experiments which have attempted to determine the exponent for the power function have come up with somewhat different results depending upon the experimental paradigm. However, the ear-matching experiments give very straight forward and rather similar types of exponents for given amounts of hearing loss as produced by white noise masking. Even if there were some inexactitude in the nature of the exponent, the protection against auditory overload which can occur with a normal hearing aid would be much greater with an aid being based upon a power function than with an aid being based upon logarithmic amplification.

ANNOYANCE

Another area in which acoustics has become increasingly interested in the human response is in the area of annoyance. Noise has become a considerable environmental problem and has obtained the interest of engineers, physicists, and psychologists. A great deal of time has been spent on obtaining measures of sound which will correlate well with ratings of annoyance by people who are exposed to the sound. A book by Schultz (1972) deals exclusively with the research used to obtain measures and the validity of these measures in predicting annoyance. This implies that the underlying dimension of interest in these measurements is no longer that of transmission loss, but rather that of change in annoyance level. The implication is that a scale related to annoyance in a manner that can be considered interval or ratio should follow the rule that equal steps on the scale should imply equal steps in annoyance. However, the work of Kryter and his associates (see Kryter and Pearson, 1963) indicate that annoyance and sound intensity are related as a power function. In fact, if correction is made for the fact that the sound was calibrated externally to the auditory meatus rather than at the ear drum, the annoyance figures of Kryter and Pearson look very much like the sone scale. This is a scale of loudness. Then decibels are certainly not related to annoyance in a one-to-one interval relationship. Nonetheless all the more prominent measures of noise meant to be related to annoyance are logarithmic scales. This is true of L_{eq}, L_{50}, Noise Pollution Level, Traffic Noise Index, etc. (Schultz, 1972). Once more, there is very little evidence that researchers in a serious way are concerned with the effects of these deviations from proper scaling procedures on the correlations which will be or are likely to be obtained with the underlying variable annoyance. Fortunately, the fact that a power function can be translated into a log-log scale means that the currently used measures are linearly related to log annoyance. Knowing this will certainly improve correlations, but nonetheless will produce interesting statistical problems when averaging over responses. For instance, if a researcher carefully measures log annoyance for each individual interviewed, averages over individuals and then takes the anti-log, he will, of course, have the geometric mean of the annoyance levels, rather than the arithmetic mean. This, of course, will underestimate the annoyance level. This is just a minor point, but illustrates problems that lack of concern with the property of scales can have. In fact, much data (Schultz, 1972) shows that although the above-mentioned measures when used in conjunction with an A-scale give fair correlations for fairly homogeneous sound spectrums, the correlations deteriorate badly for very heterogeneous sound spectrums. This would not happen using a power function rather than a log function.

Another implication of the log-log relationship is that a constant decibel decrease in sound intensity will have a greater effect upon actual annoyance levels for high intensities than it will on annoyance levels for low intensities. This is a useful consideration when one is considering the construction of sound barriers in an area in which traffic volume is apt to increase, for it implies that the relative effectiveness of the barrier will increase with an increase in traffic volume.

CONCLUSIONS

The solution to these problems is not necessarily one of actually changing sound measurement units, although the problems in converting L_{eq} to a power measure are not that great (one could imagine an annoyance level meter based upon the power function, but in every other way using parameters exactly like those meters now measuring L_{eq}). The solution to the major problem is an awareness of the relationship between the current units and the underlying variables being measured. The solution simply implies an awareness of the basic laws of measurement and the functional nature of the units of measurement that are used. When one speaks about equal intervals of units for the presentation of stimuli or for the measurement of stimuli, one should be very careful to ask what is the underlying dimension which is of interest. The example above of the parameters underlying hearing aids makes the problem more than hypothetical.

In the case of annoyance, it is possible to take the process one step further. One may ask what is the underlying dimension that is being measured when one talks about the annoyance level. Is one talking about the probability of complaint? If one is, what is the relationship between the scale of annoyance as measured by an interview and the probability of complaint. If we know this, we have gone one further step towards relating intensity level of the noise to the probability of complaint. If probability of complaint is not the underlying variable, we should decide what it is and apply proper measurement rules to it as well. Essentially sometime one must ask what is it about noise such that we wish to reduce it? How can such a dimension be scaled? What kind of scale of sound will enable people interested in the problem to work most efficiently?

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