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LOUDNESS

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I. Introduction

Loudness is the subjective intensity of a sound. Subjective means a listener must consciously respond to the sound. Intensity means the response indicates how strong the sound seems to the listener. This definition is vague, but in experiments on loudness it usually suffices to elicit consistent responses. The responses then become the basis for describing the relation between loudness and the experimentally manipulated physical and observer variables. Functional relationships replace definitions. Although this chapter can be understood without a better definition of loudness, the problem is not trivial, and the last section of the chapter takes it up again.

Loudness depends upon both the sound and the listener. The stimulus variables can be divided among four categories: intensity, spectrum, time, and background. Sound intensity is most important in determining loudness, but spectral variables like signal frequency and bandwidth must also be considered. Duration and intermittency are among the significant temporal determinants. Finally, the loudness of a sound may be strongly affected by background sound.

The stimulus variables interact with subject variables. Loudness resides in the listener, not in the stimulus. Whether the subject listens with one ear or two ears, with a fresh ear or one just exposed to noise, with a healthy or impaired ear, and whether he listens at all (pays attention)--all play a role in determining how loud a sound seems.

After discussions of the four stimulus categories and the listener come discussions of physiological correlates and of models of loudness. The last section is about the meaning of loudness and about alternative response measures such as reaction time, evoked potentials, and muscular changes.

II. Intensity

A. Loudness Function

1. Standard Loudness Function

Loudness is a monotonic function of stimulus intensity. Figure 1 gives the loudness in <u>sones</u> of a 1000-Hz tone as a function of loudness level in <u>phons</u>. Table I lists the sone values as a function of sound pressure level. Since <u>loudness level</u> is the sound pressure level of an equally loud 1000-Hz tone, the loudness level in phons of a 1000-Hz tone is the same as its sound pressure level in decibels.[1] The straight line in Figure 1 is based on the standard loudness function (ISO R131-1959). At 40 phons, a 1000-Hz tone has by definition a loudness of one sone. A sound twice as loud has a loudness of two sones, a sound half as loud, a loudness of 0.5 sones, etc. The loudness function is based on direct psychophysical procedures such as halving and doubling and magnitude estimation (see Vol. I Stevens Chapter and Stevens, 1955, 1957). The equation for the standard loudness function is a simple power law.

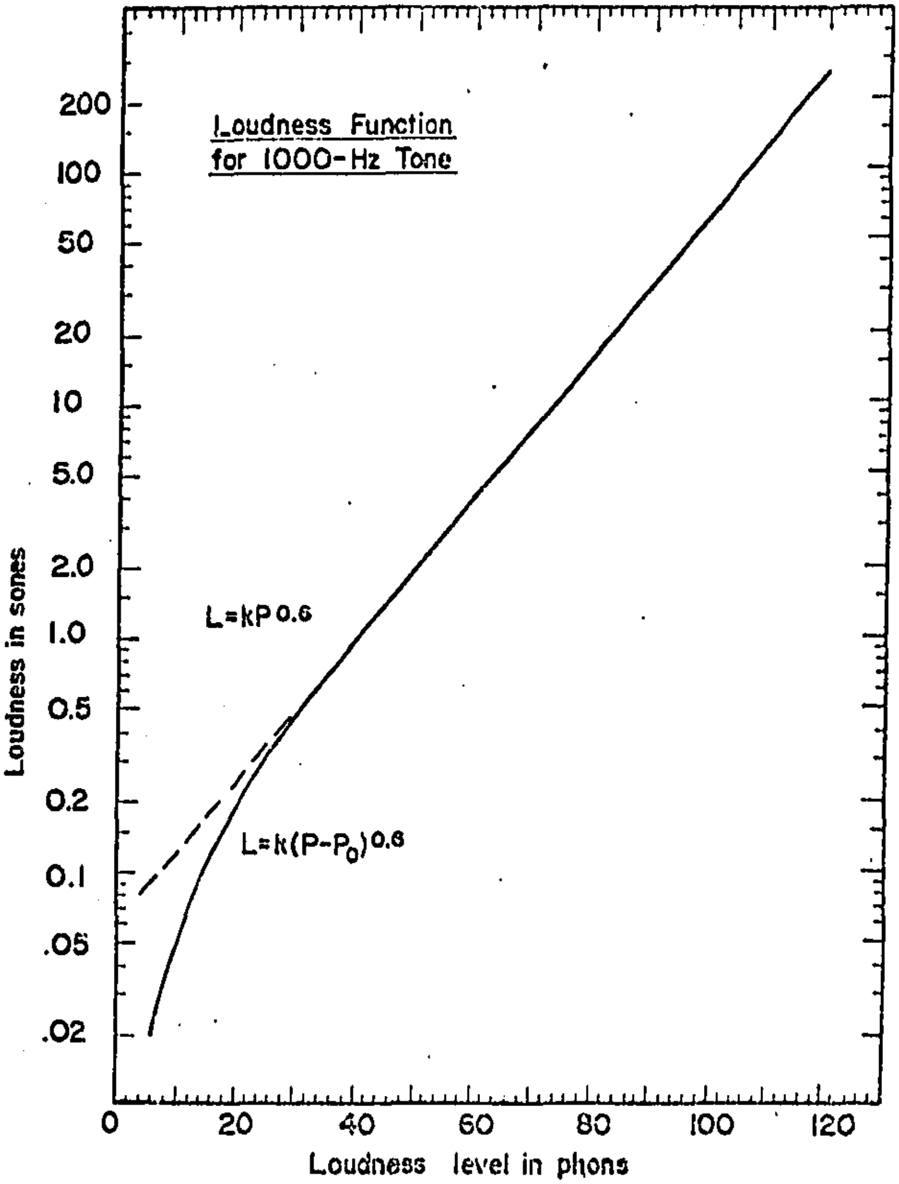

Fig. 1. Loudness of a binaural tone as a function of loudness level. (The dashed line shows how the loudness function would look were the simple power function valid down to threshold, which is around 6 phons. The solid line corresponds more closely to loudness as measured; this empirical curve is roughly approximated by the equation with a small constant, P_o, subtracted from the signal's sound pressure.)

Table I. Sone Values for 1000-Hz Tone and for White Noise

SPL dB	Tone	Noise
10	.052	-
12	.072	-
14	.095	-
15	.110	-
16	.125	-
18	.155	-
20	.190	-
22	.230	-
24	.280	-
25	.305	-
26	.330	-
28	.395	.450
30	.460	.580
32	.550	.720
34	.640	.900
35	.700	1.00
36	.750	1.10
38	.860	1.36
40	1.00	1.65
42	1.15	2.00
44	1.32	2.40
45	1.41	2.60
46	1.52	2.80
48	1.74	3.28
50	2.00	3.85
52	2.30	4.45
54	2.64	5.20
55	2.83	5.60
56	3.03	6.00
58	3.48	7.00
60	4.00	7.85
62	4.59	8.9
64	5.28	10.2
65	5.66	10.9
66	6.06	11.5
68	6.96	13.0
70	8.00	14.7
72	9.19	16.4
74	10.6	18.5
75	11.3	19.5
76	12.1	20.6
78	13.9	23.2
80	16.0	26.0
82	18.4	29.0
84	21.1	32.5
85	22.6	34.8
86	24.3	36.5
88	27.9	41.0
90	32.0	46.0
92	36.8	50.5
94	42.2	57.5
95	45.3	61.0
96	48.5	65.0
98	55.7	72.0
100	64.0	80
102	73.5	91
104	84.4	102
105	90.5	108
106	97.0	114
108	111	128
110	128	-
112	147	-
114	169	-
115	181	-
116	194	-
118	223	-
120	256	-

In equation (1) L is loudness, P is sound pressure, and k is the intercept. Plotted on the log-log coordinates of Figure 1, a power function is a straight line.

The physical magnitude of a sound may be measured in several different ways. The most common measure and the easiest to make is sound pressure. However, intensity or energy is sometimes used as the measure. Given that pressure is proportional to the square root of intensity, we can substitute $I^{0.5}$ for P in equation (1) to obtain:

$$L = kI^{0.3} \qquad (2)$$

Only the exponent and intercept change. Since pressure at the eardrums, and not sound intensity, seems to determine what happens in the auditory nervous system, the 0.6 exponent may provide a better assessment of the relation between loudness and stimulus magnitude.

In general, the power function means that equal stimulus ratios produce equal sensation ratios. Stevens shows this to be the prevailing psychophysical relationship for most sensory attributes. In particular, equation (1) means that when the sound pressure level increases 10 dB (a ratio of over 3:1), the loudness doubles. Loudness doubles regardless of the sound pressure level to which the 10 dB are added; going from 40 to 50 dB doubles the loudness of a 1000-Hz tone just as going from 100 to 110 dB. An increase of 20 dB (a ratio of 10:1) makes the 1000-Hz tone four times louder. The relative simplicity of the psychophysical function relating sensation magnitude and stimulus magnitude reflects the fundamental operating mode of all the sensory systems, a mode based on the equivalency of ratios.

The function in Figure 1 is defined for a pure tone presented in a free field, where the sound reaches the listener directly from the sound source without being reflected from any nearby surfaces. Presenting the tone through a pair of earphones does not alter the loudness function. Furthermore, the free-field and earphone functions are not altered by changing the abscissa from loudness level in phons to sensation level (SL), which is the number of decibels above threshold. The threshold for a 1000-Hz tone appears to be about the same, 6 dB SPL, whether presented through earphones or in a free field (Anderson & Whittle, 1971). So, subtracting 6 dB from the loudness levels in Figure 1 gives the sensation levels. A single threshold value simplifies the use of loudness functions plotted against sensation level and eliminates an ambiguity in the use of loudness level. Since loudness level is defined as the sound pressure level of an equally loud 1000-Hz tone presented as a plane progressive wave in the listener's frontal plane, a 1000-Hz tone presented through earphones must be equal in loudness to a tone presented in the prescribed manner. This equivalency holds for the tone presented through earphones because its threshold and loudness function are the same as in the free field.

2. Variations in the standard function

The loudness function is defined specifically for a 1000-Hz pure tone. If the frequency is changed or if a complex sound such as a band of noise replaces the pure tone, the function may change. The effect of such spectral changes is treated in Section III. A tonal stimulus implies a stimulus duration longer than about 0.5 sec. At shorter durations, it is more often called a tone burst or pulse. The standard loudness function is based primarily on tones lasting about one second. Changing the duration of the tone seems to have little effect on the shape of the function, although shortening the duration below about 100 msec reduces the loudness at a given sound pressure level, thus moving down the whole function in Figure 1. Loudness and duration are discussed in Section IV. It is also assumed that the 1000-Hz tone is presented in the quiet. A noise background usually steepens the function near threshold as shown in Section V.

The loudness function is meant to represent the responses of listeners with normal hearing who listen with both ears. If the threshold is elevated because the listener has impaired hearing or has just been exposed to noise, the function often changes as described in Section VI.

The loudness or sone function is largely based on the efforts of S. S. Stevens (e.g., Stevens, 1955) who recently (1972) suggested that a critical band of noise centered at 3150 Hz would be a better standard than a 1000-Hz tone. The loudness function for a 1000-Hz tone appears to wobble a bit, deviating from the simple power function at middle and high levels (Hellman & Zwislocki, 1961; Robinson, 1957). The function for a critical band of noise at 3150 Hz follows the power function more closely. Stevens has also presented evidence that the exponent at 3150 Hz (and also at 1000 Hz) is greater than 0.60, being more like 0.67. Since the function in Figure 1 is the international standard and is commonly used, it will serve as the reference standard in the rest of this chapter.

3. Loudness near threshold

The curved section in Figure 1 is based on Hellman's and Zwislocki's (1961) summary of their own data and those collected by a number of other investigators (Robinson, 1957; Scharf & J. C. Stevens, 1961; Zwicker, 1958). It, unlike the full straight line, shows the true course of loudness near threshold. Loudness grows more rapidly from threshold to about 30 phons than at higher levels. The solid curve in Figure 1 can be adequately approximated by a modification of the power law

$$L = k(P-P_0)^{.6} \qquad (3)$$

where P_0 is a value that approximates the effective threshold.[2] Since sound pressure first begins to have a sensory effect at threshold, the appropriate measure of the stimulus may be its distance above subjective zero, that is, threshold, rather than above physical zero. (A general discussion of other possible modifications of the power law to eliminate curvature near threshold is found in Marks and J. C. Stevens, 1968, who consider several sensory continua.)

B. Difference Limen

The loudness function tells how loud a 1000-Hz tone is at a given level. A classical question has been what is the minimum intensity difference between two sounds, otherwise identical, that allows a listener to report reliably that one sound is louder than the other. In 1928, Riesz provided the answer to this question (see also Knudsen, 1923). Riesz asked twelve listeners to detect beating between two tones set 3 Hz apart in frequency. For example, the intensity of a 1003-Hz tone was increased in the presence of a fixed 1000-Hz tone until loudness just began to fluctuate. This minimum intensity change is the just noticeable difference or ΔI. (Expressed in decibels, ΔI is a relative value equivalent to $\Delta I/I$ because decibels are the logarithms of ratios, and so a constant decibel change means that the relative increase in intensity is constant, not the absolute increase.)

At 1000 Hz, ΔI decreases from about 3 dB at 10 dB SL to less than 0.5 dB at 70 dB SL. The ΔI decreases as the tone becomes more intense at all frequencies, but at different rates. Figure 2 gives ΔI in decibels as a function of the sensation level at five frequencies. Differential sensitivity is best at higher sensation levels and at frequencies between about 1000 and 4000 Hz. Investigators since Riesz have generally confirmed his results although precise values may be somewhat different (e.g. Miller, 1947; Tonndorf, Brogan, & Washburn, 1955; Zwicker & Feldtkeller, 1967).

What is the relation between the size of ΔI and loudness? Since the detection of an intensity difference between two sounds requires that the sounds have different effects on the listener, it is reasonable to expect that those effects can be expressed in terms of loudness. Detection of a difference ought to depend on how much two sounds differ in loudness, not in intensity. It follows that the more rapidly loudness changes with intensity, the smaller the relative ΔI a listener should need in order to detect a difference between two sounds. A comparison of Figure 1 with Figure 2 shows just the opposite. For a 1000-Hz tone, ΔI is largest near threshold where loudness changes most rapidly. According to Reisz's data, a listener requires an intensity change as large as 3 dB near threshold in order to detect that a change has occurred, but requires a change of only 0.5 dB or less at levels above about 60 dB where the loudness function is flatter. Clearly, the slope of the loudness function does not predict the size of the jnd.

Translating ΔI into equivalent loudness values reveals that neither the relative loudness change nor the absolute loudness change corresponding to ΔI is constant. The absolute loudness change increases with level over the whole intensity range. The relative loudness change decreases as level increases up to about 60 dB; at higher levels it is fairly stable, varying between only 1.5 and 3%.

III. Spectrum

The loudness of a pure tone depends on its frequency as well as its intensity. The loudness of a complex sound--a sound with energy at two or more frequencies--depends on overall intensity, on the frequency of its components, and also on the distance between the component with the lowest frequency and the component with the highest frequency.

A. Equal-Loudness Contours

In a number of studies, loudness matches have been made between a 1000-Hz tone and tones at other frequencies. Three large-scale studies

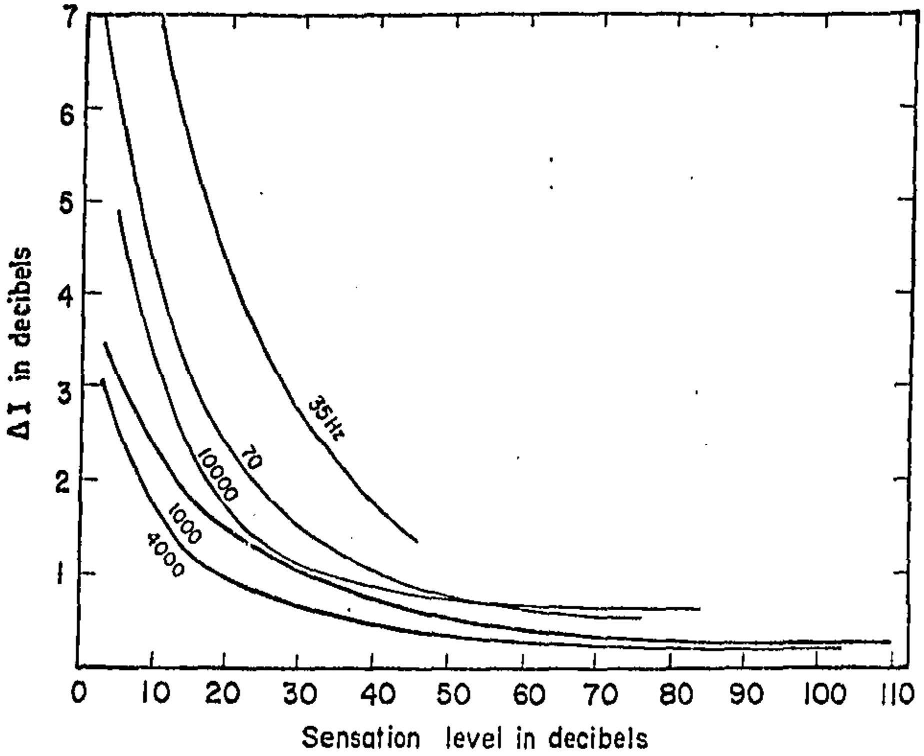

Fig. 2. The intensity difference limen, ΔI, as a function of the sensation level. [Each curve is for a pure tone at the indicated frequency. (Adapted from Stevens and Davis, 1938, p. 138, with permission of the authors.)]

are those of Fletcher and Munson (1933), Churcher and King (1937), and Robinson and Dadson (1956). Fletcher and Munson had their subjects match a binaural tone of variable frequency to a binaural 1000-Hz tone presented through earphones. Their data, the most widely cited, are presented as equal-loudness contours in Figure 3. On the ordinate is the sound pressure level at which a tone, whose frequency is given on the abscissa, sounds as loud as a 1000-Hz tone. The parameter on the curves is loudness level. All the combinations of sound pressure level and frequency on a given contour describe pure tones equal in loudness. For example, a tone at 500 Hz set to 50 dB is equal in loudness to a tone at 10,000 Hz set to 71 dB; both have a loudness level of 48 phons, which means they are as loud as a 1000-Hz tone at 48 dB SPL.[4] By showing how sound pressure level must be varied in order to keep loudness constant as frequency varies, equal-loudness contours tell us, indirectly, how loudness depends on frequency.

The bottom contour at 8 phons is the threshold curve computed by Fletcher and Munson (1933) for earphone listening. The next curve at 18 phons is nearly parallel to the threshold curve. This similarity is important because the 8-phon curve is based on threshold measurements while the 18-phon curve is based on judgments of equal loudness. Despite the gross difference in the listener's task, both sets of results reveal the same basic relation between loudness (or sensitivity) and frequency. With increasing level, however, the equal-loudness contours change shape. The large differences in sound pressure level between the low and medium frequencies lessen at higher levels. At 18 phons, a 100-Hz tone must be 37 dB more intense than an equally loud 1000-Hz tone, but at 78 phons the difference is less than 10 dB, and at 118 phons there is no difference.

Since the equal-loudness contours change shape with level and are not parallel to one another, loudness can not grow as a function of sound pressure in the same way at all frequencies. The standard loudness function for the 1000-Hz tone is not valid for every frequency. In particular, the loudness functions for the lower frequencies, where the contours bunch together, must differ from the standard function. Before examining those differences, let us look at the equal-loudness contours measured in a free field. Robinson and Dadson (1956) published a large set of data which are summarized in Figure 4.

The free-field contours differ strikingly from those measured for earphone listening at frequencies above 1000 Hz where the presence of the listener's head significantly affects the sound pressure at the eardrum. The sound pressure level shown on the ordinate is measured in an anechoic room where the specially constructed walls, floor, and ceiling reflect almost no sound. Introducing the listener alters the sound field so that the sound pressure in the ear canal is greater around 4000 Hz and smaller around 8000 Hz.

At low frequencies, the free-field and earphone contours differ less obviously, but the earphone contours do rise more steeply as frequency decreases below 1000 Hz. Anderson and Whittle (1971) ascribe this difference to low-frequency noise under the ear cushions. The noise raises the threshold for low-frequency tones, the more so the lower the frequency. The noise also reduces the loudness of suprathreshold, low-frequency tones. The loudness reduction becomes less as the level of the tone increases (see

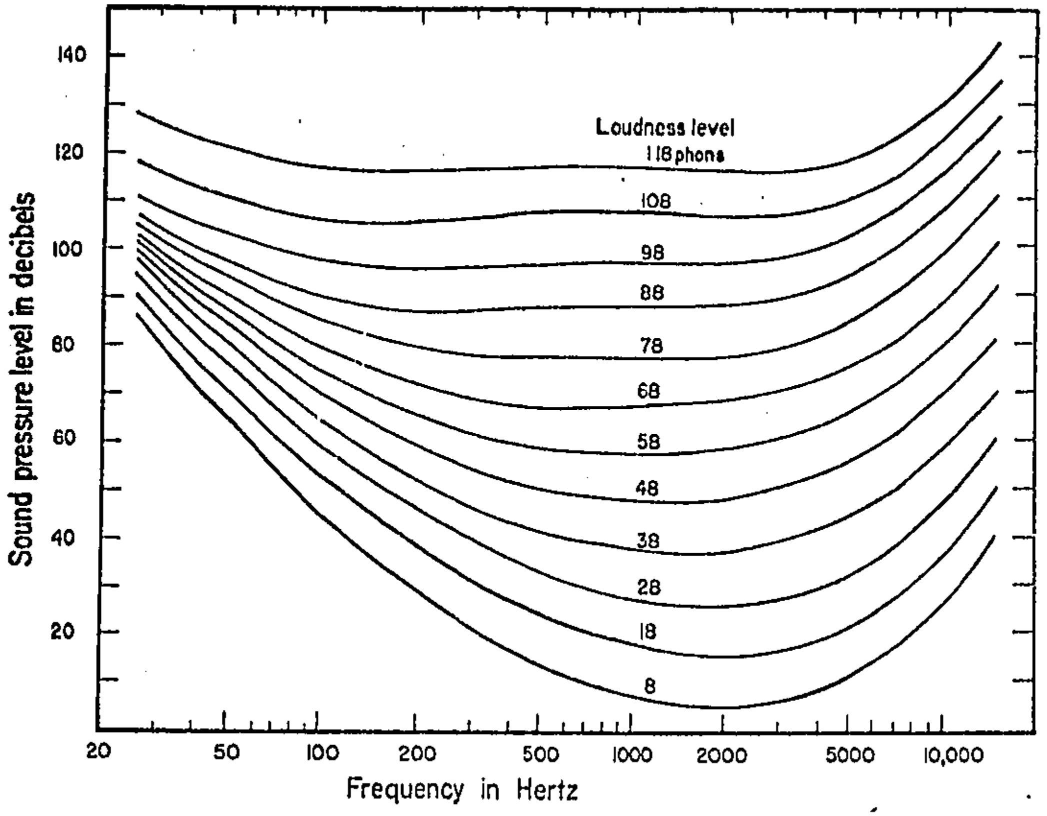

Fig. 3. Equal-loudness contours for pure tones presented through earphones. [The ordinate gives the sound pressure level required for a tone, at the frequency specified on the abscissa, to reach the loudness level indicated as the parameter on each curve. (Adapted from Stevens and Davis, 1938, p. 124, with permission of the authors.)]

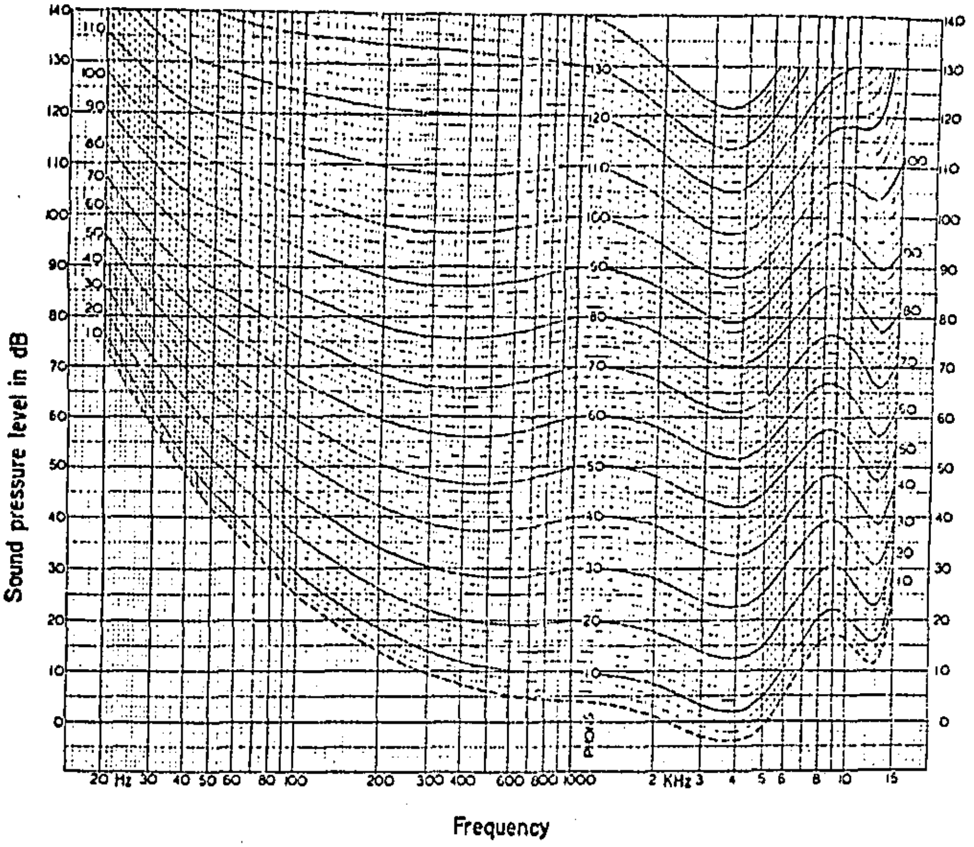

Fig. 4. Equal-loudness contours for pure tones presented in a free field. [Ordinate, abscissa, and loudness level as in Figure 3. (Adapted from ISO/R 131-1959E with permission of the original authors, D. W. Robinson and R. S. Dadson, 1956.)]

Section V). At high levels the noise has little effect, and the differences between the earphone and free-field contours at low frequencies diminish. The differences do not disappear, however, possibly because Robinson and Dadson did not use the same measuring techniques and psychophysical procedures to obtain their free-field contours as Fletcher and Munson used to obtain their earphone contours.

Unlike the contours at low frequencies, the earphone and free-field contours at high frequencies are equally dissimilar at all levels because they reflect differences in the sound pressure at the eardrum. These differences in the sound pressure generated by the earphone and in the free field are invariant with level. Were we to substitute sound pressure in the ear canal for sound pressure in the field on the ordinate of Figure 4, the new contours would become very similar to those in Figure 3 at frequencies above 1000 Hz. Such a change in the ordinate is unwarranted because sound pressure in the ear canal, being difficult to measure, is seldom known precisely in the free field.

B. Loudness Functions at Frequencies other than 1000 Hz

Loudness functions at other frequencies can be calculated from the equal-loudness contours and the standard loudness function. For a tone at a chosen frequency, each equal-loudness contour provides the loudness level of the tone and its corresponding sound pressure level. For example, the 18-phon contour in Figure 3 shows that the 100-Hz tone at 52.5 dB SPL has a loudness level of 18 phons, the 28-phon contour shows that the 100-Hz tone at 60 dB has a loudness level of 28 phons, the 58-phon contour that the tone at 75 dB has a level of 58 phons, and so forth. The loudness levels are then converted to loudness in sones from the standard function in Figure 1 or from Table I. The derived set of sound pressure levels and associated loudnesses in sones contains all the information needed to plot the loudness function for the tone at the chosen frequency.

In this manner, loudness functions were derived for tones at 100, 250, 500, 4000, and 8000 Hz. Figure 5 presents these calculated functions along with the standard function at 1000 Hz. Loudness in sones is plotted as a function of sound pressure level in decibels. Calculated functions for 2000 and 3000 Hz lie between the 1000- and 4000-Hz curves; to avoid confusion, they are omitted. The derived loudness functions are nearly congruent or parallel at frequencies above 1000 Hz where the equal-loudness contours are parallel.

The bunching of the contours at frequencies below 1000 Hz produces loudness functions at 100, 250, and 500 Hz that are steeper near their respective thresholds than is the standard 1000-Hz function near its threshold. Near their elevated thresholds, the tones at lower frequencies are softer than an equally intense 1000-Hz tone, but their loudness grows so rapidly with sound pressure as to catch up with the 1000-Hz tone at the higher sound pressure levels. Similarly steep functions for tones at 100 and 250 Hz were obtained by Hellman and Zwislocki (1968) who used the direct psychophysical procedures of magnitude estimation and magnitude production. Using magnitude estimation only, Schneider, Wright, Edelheit, Hock, and Humphrey (1972) also measured steeper functions at low frequencies. In general, steep loudness functions are associated with elevated thresholds, and, as already suggested by the low-frequency functions in Figure 5, the higher the threshold, the steeper the function.

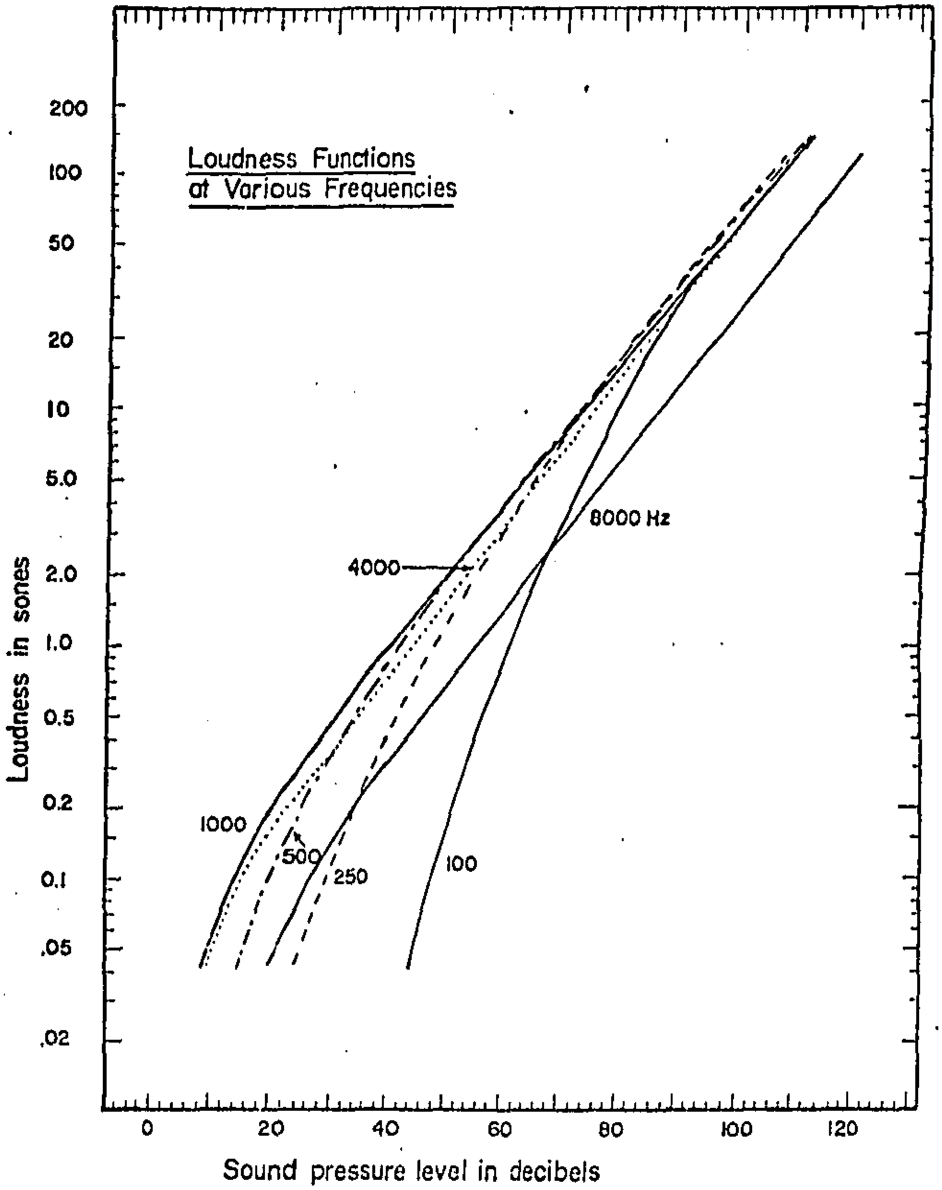

Fig. 5. Loudness of tones at different frequencies as a function of sound pressure level. (Functions are derived from the equal-loudness contours of Figure 3 and the 1000-Hz loudness function of Figure 1.)

C. Bandwidth Effects

The greater the frequency range covered by a sound (which is not close to the threshold), the louder it is. For a complex sound made up of discrete components, the frequency range is the separation in Hertz between the components with the lowest and highest frequencies. For a complex sound with a continuous spectrum, i.e., with energy at all frequencies, the frequency range is the bandwidth or distance between the lowest and highest frequencies with significant amounts of energy. (The bandwidth is usually measured between the half-power points.) Both frequency separation and bandwidth will be represented by the same symbol, ΔF. This section deals first with the relation between loudness and ΔF, and then specifically with the loudness function for white noise.

1. Loudness and ΔF

The loudness of a complex sound increases with ΔF although the sound's overall intensity is held constant. This effect is often referred to as *loudness summation*. Loudness does not begin to increase, however, until ΔF exceeds a minimum value called the *critical band* or *Frequenzgruppe* (Zwicker & Feldtkeller, 1955; Zwicker, Flottorp, & Stevens, 1957). The width of the critical band varies with the center frequency of the complex sound as shown in Table I of Scharf's review (1970a).

Figure 6 shows how the loudness level of a band of noise centered on 1000-Hz changes as a function of bandwidth. Results are similar for a complex sound comprising only two tones (Scharf, 1970a). The data in Figure 6 were obtained by having subjects adjust the level of a 1000-Hz tone until it sounded as loud as the band of noise, whose overall sound pressure level remained at the value shown on each curve. Up to 160 Hz, which is the critical bandwidth at the center frequency of the noise, loudness is independent of bandwidth. Within the critical band, loudness depends only on sound pressure level and the center frequency in a manner predictable from the equal-loudness contours (see Figure 3 or 4). This rule, however, does not apply at bandwidths narrower than about 30 Hz, where loudness fluctuations of the noise become audible; there, loudness measurements are highly variable and depend on whether the subject judges maximum loudness, average loudness, minimum loudness, or makes some compromise judgment (Bauch, 1956). Bauch's subjects, listening to three-tone complexes, mostly judged average loudness. Outside the range of audible fluctuations or beating, a complex sound whose ΔF is the same as or narrower than one critical band is equal in loudness to a pure tone at the geometric center frequency of the complex and at the same sound pressure level.

Beyond the critical band, the loudness level of a complex sound increases with ΔF except at sensation levels below 10 or 15 dB (Scharf, 1959a). At successively higher sensation levels up to between 40 and 60 dB, loudness increases more and more rapidly as a function of ΔF. But, at still higher levels, above 60 dB SPL, loudness increases progressively less rapidly with ΔF. The general rule is that loudness summation is greatest at moderate levels. Because loudness summation is a nonmonotonic function of level, the loudness of supercritical complexes, unlike mid-frequency pure tones, can not be a simple power function of sound pressure. This observation leads us to consider the loudness function for the widest possible sound, white noise.

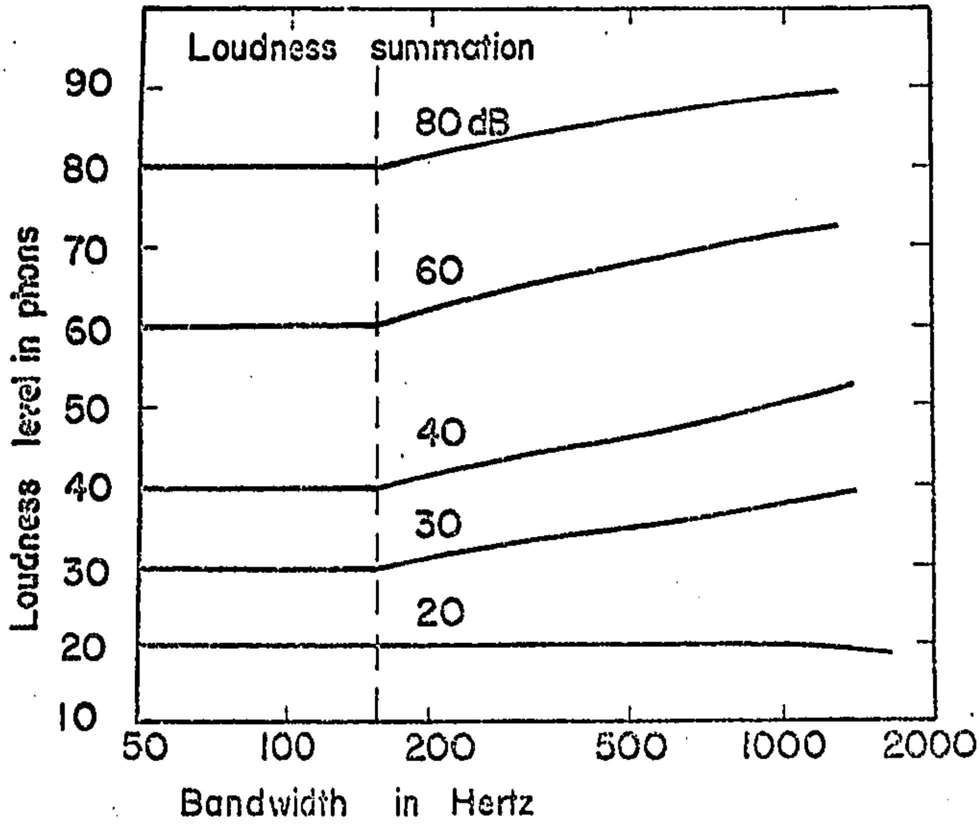

Fig. 6. Loudness level of a band of white noise as a function of its width. [Parameter on the curves is the overall sound pressure level of the noise bands. The dashed line indicates the location of the critical band for these noises centered on 1000 Hz. (Adapted from Feldtkeller and Zwicker, 1957, p. 82, with permission of S. Hirzel Verlag and the authors.)]

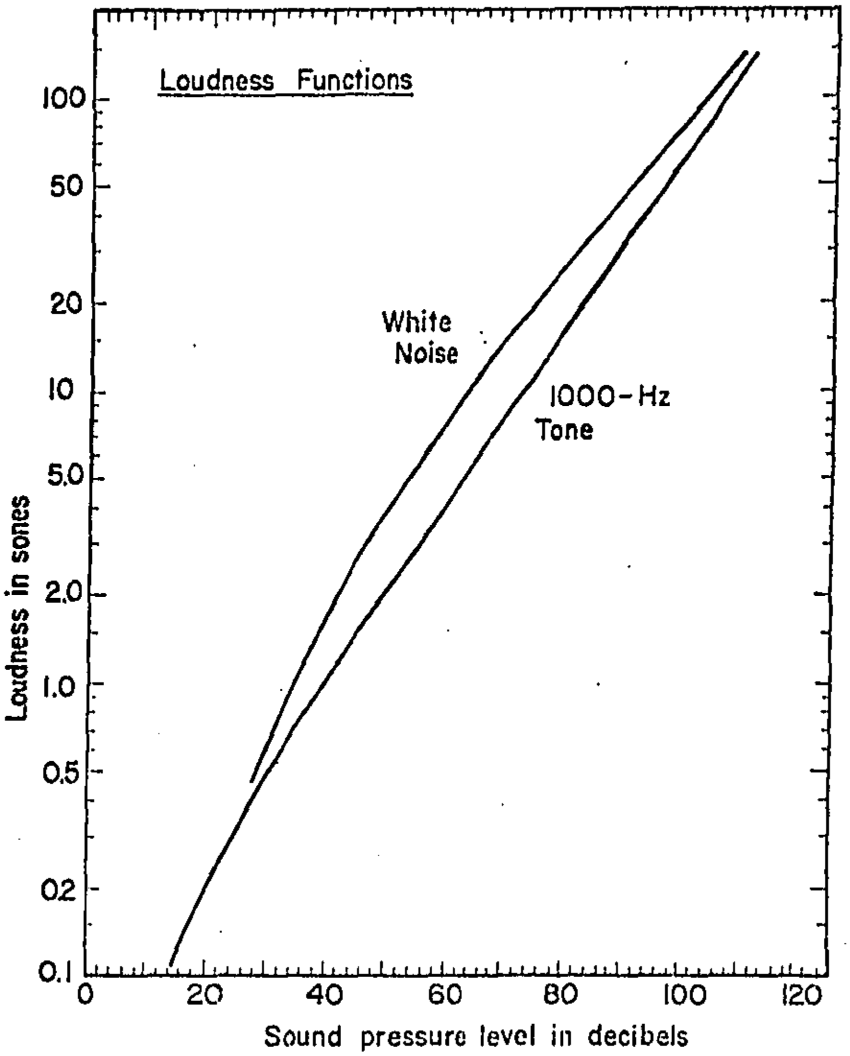

Fig. 7. Loudness of white noise and a 1000-Hz tone as a function of sound pressure level. (The tone function is taken from Figure 1.)

2. Loudness Function for White Noise

After the 1000-Hz tone, the artificial sound most often studied has been white noise. Because the threshold for white noise is about 10 dB higher than for a 1000-Hz tone (e.g. Gässler, 1954), to achieve equal loudness near threshold, the overall sound pressure level of the noise must be greater than that of the tone.

At moderate levels, however, the tone must be considerably more intense than the noise. At high levels, the tone must still be more intense in order to be as loud as the noise, but the intensity difference is smaller than at moderate levels. These basic relations have been revealed by loudness matches between tone and white noise (Brittain, 1939; Miller, 1947; Pollack, 1951; Robinson, 1953; Stevens, 1955; Zwicker, 1958) and agree with an extrapolation from matches between pure tones and bands of noise (see Figure 6).

Data based on loudness matches also agree reasonably well with direct estimates of the loudness of white noise as summarized in Figure 7 (Scharf & Fishken, 1970). Figure 7 also reproduces the tone function of Figure 1. The white-noise function was obtained by magnitude estimation and magnitude production. Subjects judged white noise and a 1000-Hz tone which were presented in a mixed order--within the same series--at eight different levels. On any given trial, the subject heard either the noise or the tone. In this way, the resulting functions for tone and noise could be directly compared. Although the measured loudness function for the tone was flatter than the standard 1000-Hz function, it was clearly a power function. The same factors that caused a flatter tone function presumably also flattened the noise function. To compensate for this distortion, the noise function presented in Figure 7 has been steepened by the same amount necessary to bring the measured tone function into accord with the standard sone function (see Figure 1).

As predicted from matching data, the white-noise function is concave downward in log-log coordinates, with a distinct mid-level bulge. Starting from its higher threshold, the noise first grows more rapidly in loudness than the tone. But the noise loses steam, and above 60 dB SPL or so, its loudness grows less rapidly. Owing to their different shapes and thresholds, the tone and noise functions must cross, probably near 25 dB SPL. At the cross point a white noise and a 1000-Hz tone are equally loud when both are at the same sound pressure level. This equality implies that the loudness of a band of noise is independent of its width when the overall sound pressure level is held constant near 25 dB. Such a finding is suggested in Figure 6 and was apparent in the multitone data of Scharf (1959a).

Although there is general agreement that the white-noise loudness function is curved relative to the 1000-Hz function (see, e.g., Stevens, 1972), the precise size of the difference in loudness between noise and tone is more difficult to determine. Loudness matches between a pure tone and white noise are highly variable, probably because matching the loudness of two such different sounds is a difficult and uncertain task. Not only is there much variability between subjects, but when subjects adjust the tone to match the noise, their judgments may differ as much as 10 dB, on the average, from their judgments when they adjust the noise (e.g. Zwicker, 1958). Also, the perceived volume or size of the white noise is much greater than that of a pure tone, which could lead to overestimation of its loudness. Both these problems may have been partly solved in the direct estimation procedure used by Scharf and Fishken (1970).

3. Secondary Spectral Factors

For multi-tone complexes, loudness level is highest when the components are evenly spaced with respect to critical bands (Zwicker, Flottorp, & Stevens, 1957). About two phons are gained by spacing the tones an equal number of critical bands apart. Similarly, loudness is greatest when the components are all about equally loud (Scharf, 1962). If the loudness of some components is reduced relative to others (without reducing the overall intensity or changing ΔF), the loudness of a supercritical sound goes down. However, loudness does not seem to change when the number of components within given frequency limits (ΔF) is increased from two to the infinite number contained within a band of white noise (Scharf, 1959b). Loudness summation is also the same whether the sound comes from a single earphone to one ear, from a pair of phones to both ears, from a single loudspeaker, or even if the lower frequencies come from one loudspeaker and the higher frequencies from another speaker (Niese, 1960, 1961; Scharf, 1973).

IV. Time

Up to about half a second, temporal variables such as signal duration and repetition rate affect loudness. Precise values for these effects are, however, often undefined owing to conflicting experimental results. This section reviews the data on duration, double pulses, and repetition rate. [The effect of rise-fall time is usually negligible (Gjaevenes & Rimstead, 1972).]

A. Duration

The study of the relation between loudness and signal duration divides into two distinct domains. In the study of brief sounds, the aim is to discover how rapidly loudness reaches maximum value as duration is lengthened from a few milliseconds to hundreds of milliseconds. In the study of loudness adaptation or perstimulatory fatigue, the aim has been to discover how rapidly loudness decreases, if at all, as duration lengthens well beyond 1 sec.

1. Brief Sounds

First, a word about thresholds. As the duration of a tone increases up to about 200 msec, threshold intensity decreases in direct proportion to time; the total sound energy, which is the product of time and intensity, thereby remains constant. This finding implies that the ear integrates energy over time up to about 200 msec. Knowledge of the auditory system suggests very strongly that the ear integrates neural energy, not acoustical or mechanical energy (Zwislocki, 1969).

The auditory system integrates neural energy also at suprathreshold levels where loudness replaces threshold or detectability as the response variable. In the typical experiment, listeners make loudness matches between short-duration and long-duration stimuli. Results are treated by plotting the intensity of the brief sound, at which it is judged equal in loudness to the standard sound, as a function of its duration. Figure 8 is one such plot (Port, 1963a). The sounds were third-octave bands of filtered white noise, and the standard was at 60 dB SPL. Since all the loudness matches were made to the same long-duration stimulus, the data map out an equal-loudness contour, which is approximated by the solid line.

We can pose three questions about such data. At what duration does intensity become constant and independent of duration? Before becoming constant, how does intensity change as a function of time, i.e., what is the trading relation between intensity and time? Does the shape of the contour depend on stimulus variables such as frequency, level, and bandwidth? Answers to these questions have been many and varied. Table II summarizes them, first for white noise and then for pure tones, mostly at 1000 Hz.

The column labelled trading relation indicates whether (a) intensity changed in direct inverse proportion to time thus maintaining constant sound energy (as at threshold), (b) intensity changed more rapidly than time so that energy decreased as time increased, or (c) intensity changed less rapidly so that energy increased with time. The next column gives the duration at which intensity became constant. Usually, the equal-loudness contour showed a rather gradual transition from a decreasing to a constant intensity, so that the values for the critical duration are not precisely defined. The next column gives the value of the time constant, τ, calculated by the experimenter for his data from an exponential function of the form, $I(t) = I_{\infty}/(1 - e^{-t/\tau})$, where I_{∞} is the asymptotic intensity at long durations, t, of the sound. The exponential function does not exhibit a sharp discontinuity, and would fit the data in Figure 8 somewhat better than the solid lines do. However, the pictured discontinuity may be real.

Variability among subjects in their critical duration or trading relation would smear the discontinuity and produce a slow transition. Accordingly, the calculated time constant and measured critical duration can both be treated as estimates of the same discontinuity in an intensity-by-time contour having two expressions, each equal to a constant.

(for $t \leq CD$: $I \times t = K$) (This first expression becomes more complicated if the equal-energy rule does not hold.)

(for $t \geq CD$: $I = K'$)

Table II reveals no striking differences between the trading relations and critical durations or time constants measured for white noise and those measured for pure tones. This finding is consistent with the observation that loudness increases as a function of bandwidth or ΔF in the same way whether a sound lasts a few milliseconds or hundreds of milliseconds (Port, 1963a; Scharf, 1970b; Zwicker, 1965). Nevertheless, the large variability among the measurements in Table II may obscure real differences. For both tone and noise, the measured trading relation has revealed all three possibilities: increasing, decreasing, and constant energy. The critical duration or time constant also varies over a wide range of values, but has almost always been 150 msec or less. The effect of sound level is unclear.

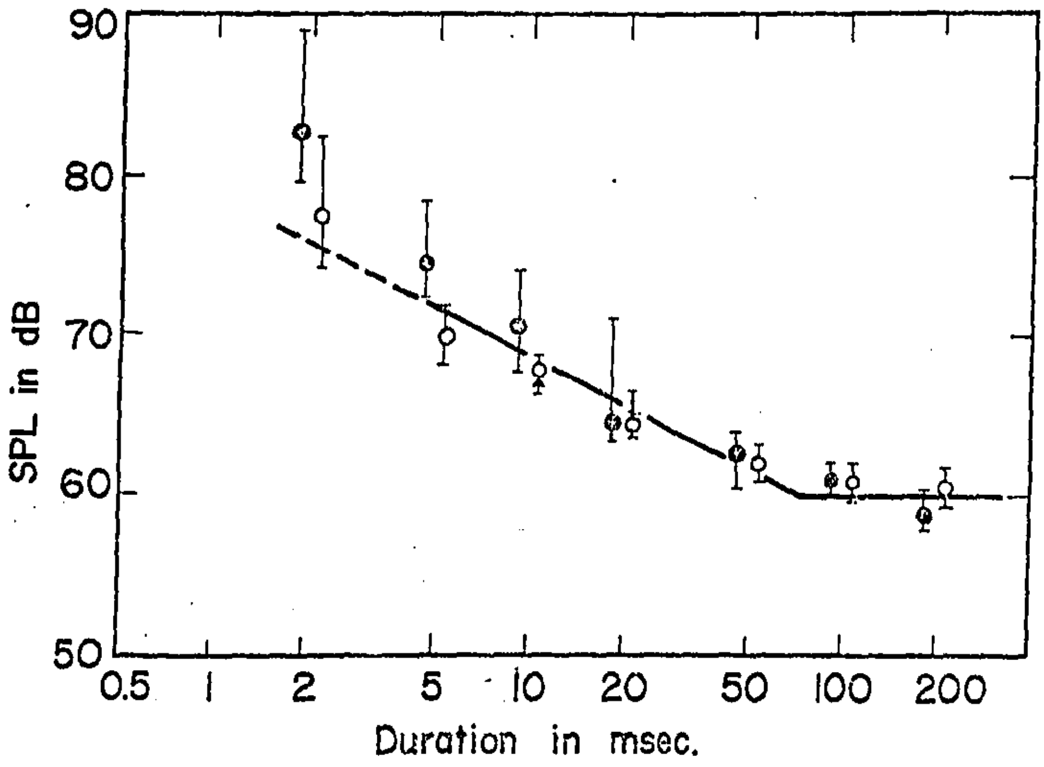

Fig. 8. Sound pressure level at which narrow-band noise at various durations is judged equal in loudness to a long-duration band at 60 dB SPL. (Port, 1963, adapted with permission of *Acustica*.)

Table II. Summary of Studies of how Loudness Varies as a Function of Duration

Author(s) & Year	# Subjects	Stimulus	Rise-Fall Time (msec)	Trading Relation*	Critical Duration** (msec)	Time Constant (msec)	Effect of level
Miller, 1948	3	white noise	abrupt	energy increases	60-140	-	critical duration (CD) decreases as level increases
Pollack, 1958	7-10	white noise	abrupt	energy constant	100	-	-
Small, et al., 1962	12	white noise	-	energy decreases	15-50	-	CD decreases as level increases
Stevens & Hall, 1966	12	white noise	-	energy decreases	150	-	none
Zwicker, 1966	83	white noise	abrupt	energy constant	200-400	100	-
	74	1000 Hz	1-2	energy constant	200-400	100	-
Békésy, 1929	-	800 Hz	abrupt	energy increases	120-180	-	CD shorter at higher level
Ekman, et al., 1966	10	1000 Hz	10	energy increases	over 500	-	steeper trading relation at high levels
Garner, 1949	6	1000 Hz	abrupt	energy increases	500	-	steeper trading relation at higher level
Munson, 1947	-	125, 1000, 5650 Hz	3	energy decreases	200	-	steeper trading relation at higher level

Table II. (cont.)

Author(s) & Year	# Subjects	Stimulus	Rise-Fall Time (msec)	Trading Relation*	Critical Duration** (msec)	Time Constant (msec)	Effect of level
Niese, 1956	12	500, 1000, 3000 Hz	abrupt	energy constant	65	23	–
Niese, 1959	10	1000 Hz	1-2	energy increases	100	23	none
Pedersen & Lyregaard, 1972	300	1000 Hz	1-2	energy constant	160-320	70-100	none
Reichardt & Neise, 1970	50	1000 Hz	3	energy constant	100	30	–
Port, 1963a	8	narrow-band noise at 350, 2000, 10,000 Hz	1-2	energy constant	70	70	none

* Trading relation refers to the relation between intensity and time. As stimulus duration increases up to the critical duration, to keep loudness constant, total sound energy (I x t) has been found to remain constant, decrease, or increase.

** For constant loudness, intensity must be reduced as duration is increased up to the critical duration.

(A dash means the information either was not relevant to the study or was not provided.)

Some studies show no effect on either the critical duration or trading relation. Other studies show a decrease in the critical duration with increasing level. A few studies suggest that the higher the level, the more rapidly intensity decreases as duration increases. Frequency seems to have little, if any, effect. Signal frequency was varied in three studies (Munson, 1947; Niese, 1956; Port, 1963a), and only Port noted a frequency effect, a lengthening of the critical duration at 10,000 Hz.

Owing to the disagreement in the data and to the importance of a time constant in the calculation of loudness and assessment of noise, an international experimental program has been underway in over twenty laboratories to try to achieve some consensus on the relation between loudness and duration. Pedersen and Lyregaard (1972) have presented some preliminary results, which are summarized in Table II. Unfortunately, results from different laboratories seem to be quite divergent despite uniform experimental conditions and procedures.

Investigators come up with so many different conclusions about the relation between loudness and duration mainly because matching the loudness of a brief sound to a long sound is difficult. The outcome is readily affected by variations in experimental parameters such as the interstimulus time, repetition rate, and difference in the duration of the variable and standard sounds (Reichardt, 1965). Possibly the auditory system handles temporal factors differently from person to person. More likely, normal listeners vary because they use different criteria in their loudness matches, rather than because their auditory systems differ significantly. Some listeners may have trouble abstracting the loudness of a sound from its subjective duration, others may be confused by what Reichardt (1965) calls a roughness component.

Criterion differences are especially important when the stimuli are tone bursts. As its duration is shortened, a tone steadily loses its pitch and tonal quality, partly because the auditory system does not have time enough to build a full pitch percept and partly because an increasing portion of the sound energy falls at frequencies other than that of the original long-duration tone. The effective bandwidth of a tone, which is turned on and off abruptly, increases in nearly direct inverse proportion to duration. Spectral changes contribute to the variability of the loudness judgments by making the sounds more dissimilar and thereby harder to match in loudness. (The increase in bandwidth is usually too small to influence loudness directly, in the manner described in Section III C; unless the duration is shortened to less than 1 to 10 msec, depending on frequency, almost all the sound energy remains confined to a single critical band.)

Two of the studies in Table II did not require subjects to match short and long sounds for equal loudness. Ekman, Berglund, and Berglund (1966) and J. C. Stevens and Hall (1966) had their subjects make magnitude estimations of the loudness of signals presented at various durations and levels. These results provided a direct measure of how loudness increases with duration. Ekman et al. found that the loudness of a pure tone increases as the logarithm of duration, with the rate of increase faster at higher than at lower levels. Stevens and Hall found that the loudness of white noise increases at all levels as the 0.35 power of duration.

The data vary so much, it is difficult to say how the loudness function looks at short durations. Only Stevens and Hall (1966) seem to have directly measured loudness functions for sounds (white noise) of different durations. They found that signal duration had no effect on the exponents of the power functions they fitted to their data. (Actually, the data would be better fitted by a bowed function similar to the one in Figure 7.) Close to threshold, however, the loudness functions ought to become steeper as duration shortens because the critical duration at threshold is almost certainly longer than at suprathreshold levels. Furthermore, if the critical duration continues to decrease as level increases well above threshold, as many studies suggest, then the short-duration loudness functions ought to be steeper up to fairly high levels, not only near threshold. A complicating factor is the slope of the equal-loudness contour, i.e., the trading relation between time and intensity, which may become steeper at higher levels. Such a change would flatten the loudness functions at short durations. The critical duration and the trading relation could change with level in opposite directions to produce invariant loudness functions at short durations. Given the many uncertainties, no firm conclusion is possible about the slope of loudness functions at short durations.

2. Long-duration Stimuli

Loudness first reaches full value a fraction of a second after the onset of stimulation. Does loudness then remain steady or decrease? Is there loudness adaptation? A number of recent studies have revealed little or no decline in the loudness of sounds lasting as long as twelve minutes (Bray, Dirks, & Morgan, 1973; Fraser, Petty, & Elliott, 1970; Mirabella, Taug, & Teichner, 1967; Petty, Fraser, & Elliot, 1970; Stokinger, Cooper, & Meissner, 1972; Wiley, Small, & Lilly, 1973). Loudness adaptation in normal listeners is absent at all frequencies and at levels at least as high as 70 dB. Consequently, the loudness function in Figure 1 is valid for any binaural 1000-Hz tone whose duration exceeds about 200 msec.

Results of some studies of "perstimulatory adaptation" have been interpreted as evidence for loudness adaptation. However, adaptation occurs only when binaural interaction is possible, i.e. when sounds are presented simultaneously, or nearly so, to the two ears. The observed adaptation involves primarily lateralization but not loudness (see Ward, 1973, pp. 334-337, for a cogent review and relevant references).

B. Double Pulses

The loudness of two tone bursts, each lasting less than 10 msec, depends on the time interval separating them. At brief intervals of 1 or 2 msec, the loudness level of two bursts is 3 phons higher than the level of either one alone. As the interval lengthens this advantage decreases, disappearing altogether, according to some data, when the interval reaches 25 msec (Niese, 1956) or 30 msec (Schwarze, 1963). Other data suggest that there is some loudness summation or enhancement up to intervals as long as 200 msec (Irwin & Zwislocki, 1971; Scharf, 1970b). The 200-msec estimate is based also on data for two tones very different in frequency, which have as much as a 10-phon advantage in loudness level at brief temporal separations. Such a large difference in loudness level made it possible to trace the decay of loudness over time more precisely than the 3-phon difference measured with identical stimuli. Apparently, then, loudness summates over a longer time period for two tone bursts separated by a silent interval than for a single burst. The inserted silent interval may permit recovery from inhibitory off-effects (Zwislocki, 1969). (The near absence of such post-stimulus inhibitory effects at threshold may be why the critical duration at threshold is longer than above threshold.) Another possibility is that the loudness of two successive pulses is largely the result of an enhancement of the loudness of the second pulse by the first; such an enhancement may have been demonstrated in dichotic presentations (Galambos, Bauer, Picton, Squires, & Squires, 1972).

C. Pulse Trains

A pulse repeated over and over has a repetition or pulse frequency expressed in pulses per second (pps). Several investigators have measured the loudness of a pulse train as a function of its frequency (Garner, 1948; Niese, 1961; Pollack, 1958; Port, 1963b). Their subjects matched a continuous tone or noise to the interrupted sound. When the pulse frequency equals 1/T, where T in seconds is the duration of each single pulse, then the interrupted sound is indistinguishable from a continuous sound. [For example, a 10-msec (.01 sec) burst repeated 100 times per second is a continuous sound.] At 1/T, the "interrupted" sound is set to the same level as the continuous sound for equal loudness. At slower frequencies, the interrupted sound must have a higher level for loudness to be equal.

At pulse frequencies so slow that only one or two brief pulses are presented each second, the duration of the pulse determines how much higher the level of the interrupted sound must be. The shorter the pulse, the larger the difference. For a given duration, however, the level difference reaches its maximum at between 2 and 5 pps; slowing the frequency below 2 pps has no effect on the loudness of the interrupted sound. Further reduction of the pulse frequency is ineffective because at 2 pps, the individual pulses are already almost 500 msec apart, beyond the range of loudness summation as already noted in studies of double pulses.

As pulse frequency slows from its maximum value, 1/T, to its lower effective limit, near 2 pps, the level of the interrupted sound increases too slowly to maintain constant sound energy. The interrupted sound requires less energy than an equally loud steady sound. (Energy is computed over the whole presentation period, including the silent intervals.) Hence, for a given amount of sound energy, greater loudness is attained by distributing the energy over time with interspersed silent intervals than by making it a continuous sound. Perhaps the advantage comes from a reduction of post-stimulus inhibitory effects during the silent intervals.

V. Background

In the quiet a 1-sec, 1000-Hz tone at 80 dB SPL has a loudness of 16 sones and is loud. Heard against a 90-dB white noise, the same 80-dB tone is soft. The reduction of loudness by a background noise is called partial masking, to distinguish it from complete masking, in which the noise makes the signal inaudible. A masking sound, then, raises the threshold for the signal and reduces its loudness. At the same time, the masker makes the loudness function for the signal steepens and the more intense the masker, the steeper the loudness function (Chocholle & Greenbaum, 1966; Hellman & Zwislocki, 1964; Lochner & Burger, 1961; Scharf, 1964; Stevens & Guirao, 1967). Partial masking depends not only on the intensity of the masker, but also on its bandwidth and its frequency location relative to the frequency of the signal. Each of these factors is treated in turn.

A. Intensity of Masker

Figure 9 presents some of the data collected by Stevens and Guirao (1967). The listeners adjusted a 1000-Hz tone in the quiet to match in loudness a 1000-Hz tone presented against a white noise. The noise was set at the level given as the parameter on the curves. If the noise had no effect on the loudness of the tone, the data would fall on the dashed line where the levels of the unmasked and masked tones are equal. Stevens and Guirao drew the solid lines through the data on the basis of a model that included the following three assumptions. (1) A tone in noise must be more intense than an equally loud tone in the quiet, but the intensity difference decreases as the level of the partially masked tone increases. In other words, the loudness of the tone in noise grows more rapidly than the loudness of the tone in quiet. (2) Loudness grows more rapidly in noise up to a level 30 dB above the effective masked threshold for the tone. Above 30 dB the loudness of the tone in noise grows at the same rate as the loudness of the tone in quiet; the solid line is then parallel to the dashed line. (3) The more intense the noise, the steeper the function. Although not predicted by the model, it turned out that the tone in noise must be more intense than the equally loud tone in quiet, even at high signal levels where the noise no longer steepens the function. Zwicker (1963) noted a similar failure of a tone in wide-band noise to attain normal loudness.

By means of the standard sone values in Table 1, the data of Stevens and Guirao were converted to sones. Figure 10 presents the loudness of the 1000-Hz tone in noise as a function of the sound pressure level of the tone. These curves are based on the data in Figure 9 and on other data, which Stevens and Guirao obtained by having listeners adjust the tone in noise to match the tone in quiet. The slope of the loudness functions in Figure 10 increases monotonically with the level of the masking noise. Put another way, the higher the masked threshold for the tone, the steeper its loudness function up to about 30 dB above threshold.

No attempt was made to draw the loudness functions in Figure 10 with a sharp change of slope at a level 30 dB above threshold. Stevens and Guirao suggested such a discontinuity, but most available data do not show it, perhaps because averaged data tend to obscure discontinuities. Nevertheless, it is clear that within about 30 dB of the masked threshold, the loudness function is steeper; at higher levels it has the usual slope of about 0.6. The question remains whether the transition zone is smooth or sharp.

The corrected power law, $L = k(P-P_0)^{0.6}$, does not appear to provide a good fit to these masked functions. In general, a simple modification of the power function is insufficient. Stevens (1966) has suggested that

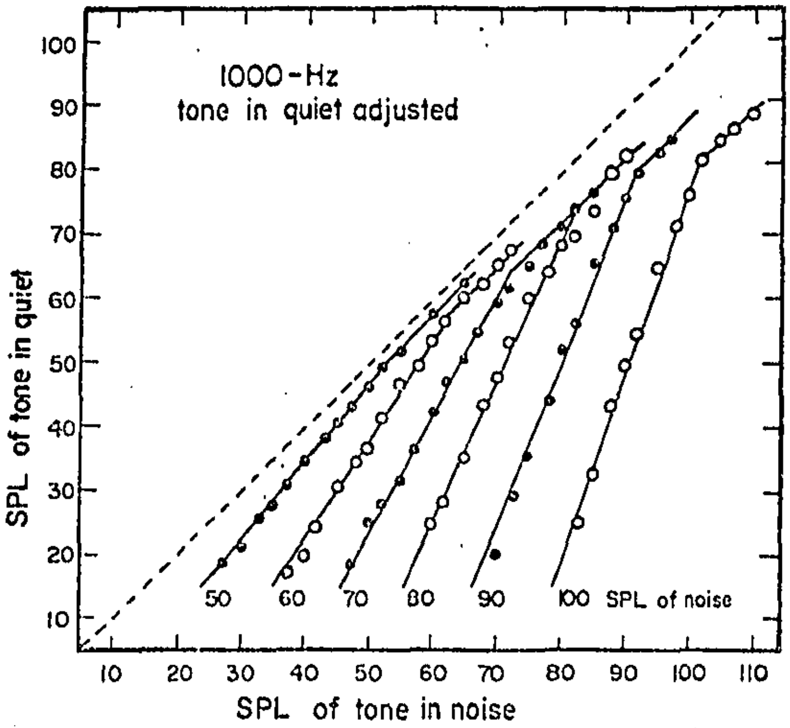

Fig. 9. Sound pressure level at which a tone in quiet is judged equal in loudness to a tone partially masked by white noise. [Parameter on the curves is the level of the masking noise in decibels. Symbols are filled and unfilled for clarity (Stevens and Guirao, 1967, adapted with permission of <u>Perception and Psychophysics</u>).]

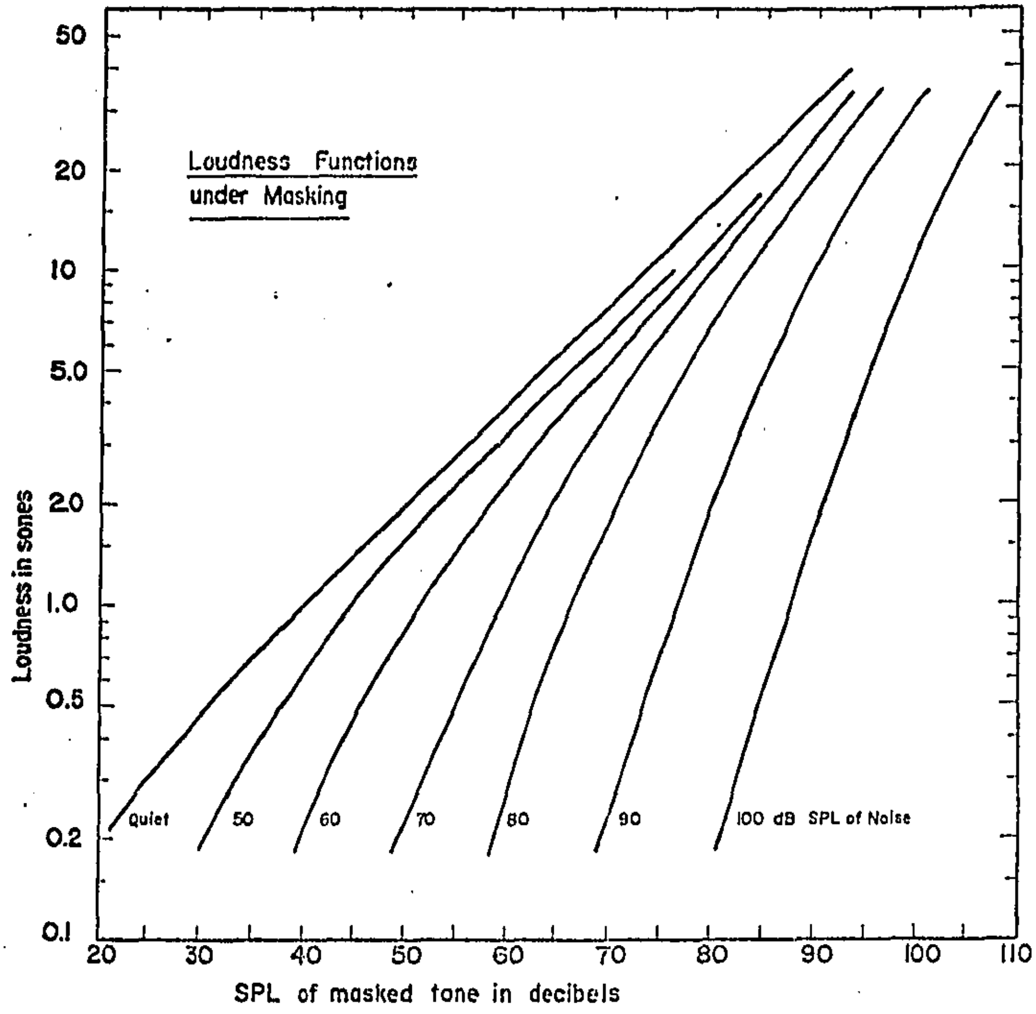

Fig. 10. Loudness as a function of the sound pressure level of a 1000-Hz tone partially masked by white noise. [Curves are derived from the loudness matching data of Stevens and Guirao (1967) and the standard loudness function in Figure 1.]

in masking, as in other cases of elevated thresholds, such as in deafness and for low-frequency tones, the relation between loudness and intensity undergoes a power transformation, in which the slope of the function decreases abruptly at some level above threshold. Zwicker (1963) and Zwislocki (1965) have suggested other modifications.

That noise steepens the loudness function was first quantitatively demonstrated by Steinberg and Gardner (1937) in a paper that pointed out the similarity with loudness recruitment in certain types of deafness. Loudness recruitment refers to the abnormally steep growth of loudness so clearly shown in Figure 10. Recruitment in hard-of-hearing listeners is discussed in Section VI C.

B. Bandwidth

The slope of the loudness function under masking increases when the bandwidth of the masking noise is narrowed (Hellman, 1970; Zwicker, 1963). This rule holds provided the frequency of the masked tone remains within the frequency limits of the masking band. Heard against a masker one critical band wide or narrower, the loudness of a tone grows so rapidly that it reaches its normal value at a level 10 to 15 dB above the masked threshold. Heard against a noise wider than a critical band, the tone may never reach normal loudness. Nevertheless, the slope of the loudness function does become normal at some point: in white noise at about 30 dB above threshold.

Bandwidth is also a relevant variable when the noise is the signal and a pure tone is the masker. The tone masks a narrow-band noise somewhat better than it masks a wide-band noise. In both cases, however, the tone is a much less effective complete and partial masker, by about 20 dB at high intensities, than an equally loud narrow-band noise (Hellman, 1972).

C. Frequency Relations between Masker and Signal

How much one sound masks another depends very much on their frequency relations. Figure 11 shows how a narrow band of white noise reduces the loudness of a pure tone whose frequency is given on the abscissa. The noise, set at 70 dB SPL, was one critical band wide and centered on 1000 Hz. The parameter on the curves is the loudness level to which the masked tone was set, so that all points on a given contour were equally loud. The top contour is the threshold curve. The ordinate shows masking in decibels, defined as the amount by which the sound pressure level of the masked tone had to be increased, owing to the presence of the noise, in order for the tone to reach the given loudness level.

The spread of masking is the same at threshold as at 15 phons. But as the loudness level increases, the pattern becomes less skewed toward the lower frequencies. This change means that at low loudness levels, a given noise is more effective in completely or partially masking higher-frequency tones, whereas at high levels it is more effective in masking lower-frequency tones. Put another way, the loudness functions for tones lying above the frequency limits of the noise are steeper than the functions

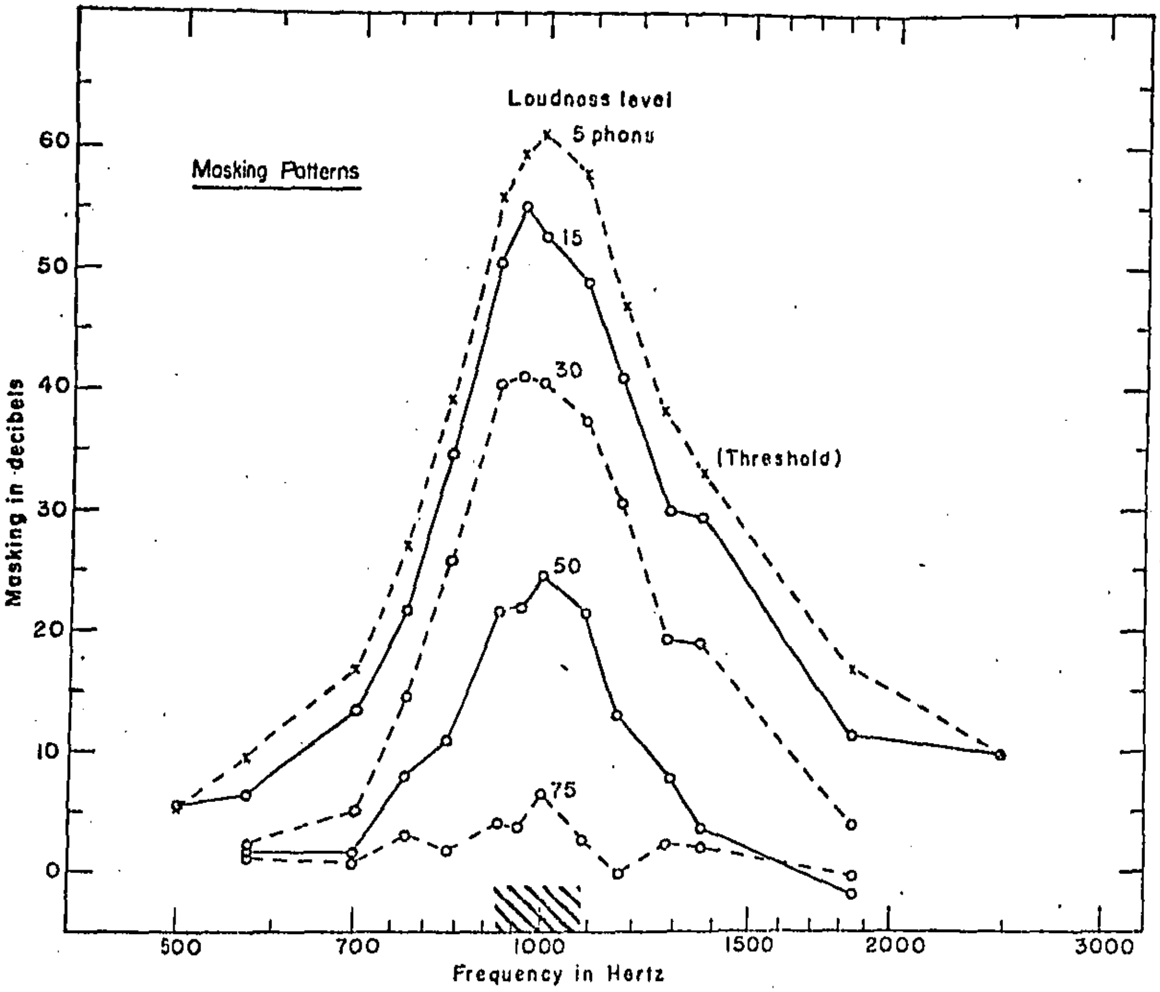

Fig. 11. Masking of pure tones by a narrow-band noise centered on 1000 Hz and set at 70 dB SPL. [Masking is the difference between the sound pressure level of the masked tone and that of an unmasked tone when judged equally loud. The loudness level of the masked tone, measured by matching it to the unmasked tone of the same frequency, is the parameter. Hatched area gives the ideal spectral limits of the masking noise. Data are based on four subjects (Scharf, 1971, adapted with permission of Audiology).]

for tones lying the same distance in frequency below the noise. Once again, steeper loudness functions are associated with higher thresholds. These relations hold as well for a masking noise at 90 dB SPL and for a subcritical band of noise (Scharf, 1971). Similar results have been obtained for a pure tone partially masking another pure tone (Chocholle & Greenbaum, 1966).

VI. Listener

People hear in much the same way, permitting a large number of generalizations about loudness with hardly a reference to the listener. Nevertheless, listeners do differ from one another; and the same person's judgment may change from one time to another. It makes a difference whether the subject listens with one ear or two ears, and whether or not he has recently been exposed to loud sounds. Both these factors can be controlled by the experimenter. Factors outside of experimental control include pathology of the auditory system and normal individual differences. Normal differences may include small physiological variations in the auditory system and complex variations in those aspects of decision making and personality that could affect the judgment of sound. This section deals with each of these factors in turn--binaural loudness, fatigue, deafness, and individual differences.

A. Binaural Loudness

A sound is louder in two ears than in one. The question that has intrigued investigators for many years is how much louder. The most recent answer is that a pure tone or narrow-band noise is about 1.7 times louder in two ears than in one (Scharf & Fishken, 1970). A wide-band noise, such as white noise, is also about 1.7 times louder in two ears on the average, but the ratio of binaural-to-monaural loudness increases with sound-pressure-level until at high levels it may be 2:1.

An invariant binaural-to-monaural ratio means that the binaural and monaural loudness functions for pure tones have the same slope; only the intercepts differ. The ratio of the intercepts in the power function, $L = kP^n$, is equal to the ratio of binaural to monaural loudness. Accordingly, the loudness function of Figure 1 holds for both binaural and monaural tones, except that the monaural curve should lie about 8 phons to the right of the binaural curve at loudness levels higher than 40 phons and less than 8 phons to the right at lower loudness levels. The white-noise function in Figure 7 is for binaural loudness. The monaural function for noise has a similar bowed shape, but lies to the right of the binaural function; the decibel difference between the two functions increases with sound pressure.

The data of Scharf and Fishken are based on magnitude estimation and production. The tonal data agree with those of Hellman and Zwislocki (1963) who used similar procedures to measure the binaural and monaural loudness of a 1000-Hz tone. The data on white noise differ somewhat from those of Reynolds and Stevens (1960) who used a moderately wide band of noise; they measured a larger binaural-to-monaural ratio which increased more rapidly with level.

The conclusions of Scharf and Fishken also agree with most of the matching data in the literature (Caussé & Chavasse, 1942; Porsolt & Irwin, 1967; Scharf, 1968). Only the matching data of Fletcher and Munson (1933) suggested a larger binaural-to-monaural ratio for a pure tone. Their overestimation was constant across frequency, which shows that binaural loudness summation is independent of frequency. Scharf (1969) went further to show that loudness summation is the same even when the tone in one ear differs greatly in frequency from the tone in the other ear. This dichotic summation of loudness is the same in different parts of the frequency spectrum.

While independent of frequency differences between the two ears, binaural loudness summation is not independent of intensity differences. Irwin (1965) showed that binaural summation is most efficient when the sound power is about equal in the two ears.

Given a constant binaural-to-monaural loudness ratio, the monaural loudness function for a pure tone or narrow-band noise can be derived from the standard binaural function by changing the value of k so that $L_m = 10^{.45}/17.7$ (P [illegible] $4P_o)^{0.6}$, where L_m is monaural loudness in sones, P is the sound pressure of a 1000-Hz tone, and P_o is the correction factor used in the binaural formula. (Because the monaural threshold is 3 dB higher than the binaural threshold, the value of P_o is increased by the corresponding ratio.)

B. Auditory Fatigue

A loud sound fatigues the ear. Auditory fatigue has been demonstrated many times as a temporary increase in the normal threshold, known as the temporary threshold shift (TTS). Near an elevated threshold, loudness must be depressed; there is also a TLS or temporary loudness shift.

Short exposure to very intense sounds or long exposure (measured in years) to weaker sounds may result in a permanent threshold shift and a permanent loudness shift, a condition dealt with in the section on auditory pathology.

The reduction in loudness caused by a fatiguing sound is analogous to partial masking, except that the masking sound is turned off at least several seconds before the signal is turned on. The asynchrony of masker and maskee reduces the threshold shifts and changes their pattern. Instead of maximum loudness reduction and threshold elevation at the same frequency as the fatiguing sound, the maximum TLS and TTS are at a frequency a half octave higher (Davis, Morgan, Hawkins, Galambos, & Smith, 1950).

Riach, Elliott, and Reed (1962) measured the loudness function for a 2800-Hz tone four minutes after one ear had been fatigued by a 2000-Hz tone. Presented between 100 and 110 dB SL, the fatiguing tone was left on long enough to raise threshold 10, 20, or 30 dB. Magnitude estimation of the 2800-Hz tone presented separately to the fatigued and rested ears showed that the loudness function was steeper in the fatigued ear up to about 60 dB above the normal threshold. Above 60 dB SL, the loudness functions were approximately the same in both ears. Here is clear evidence of loudness recruitment like that shown in Figure 10. And the greater the TTS, the steeper the function; the slope of the lower part of the loudness function increased from .62 to 1.06 as TTS increased from 10 to 30 dB. Once again higher thresholds mean steeper loudness functions. Davis et al. (1950) and Hickling (1967) have reported similar evidence for loudness recruitment after exposure to noise.

The strong effects of fatigue on loudness may seem at variance with the lack of loudness adaptation. If a sound can be turned off and still reduce the loudness of another sound presented four minutes later, then the fatiguing sound ought to reduce its own loudness during continuous stimulation. However, the fatiguing sound reduces the loudness only of sounds at intensity levels much lower than its own. The published curves of Riach et al. show that for loudness to be reduced the judged tone has to be at least 40 to 50 dB weaker than the fatiguing tone. Furthermore, the fact that the loudness function under fatigue is steeper than the normal function means that the reduction of loudness is greatest near threshold. Perstimulatory loudness adaptation apparently does not occur because the level of the "test" sound (later segment of a sound) is too high relative to the level of the "fatiguing" sound (early segment).

C. Auditory Pathology

Changes in the loudness function have long been important in the clinical diagnosis of auditory pathology. Loudness recruitment (a term first used by Fowler, 1928) often occurs in cochlear pathology but seldom in either conductive or neural pathology (Steinberg & Gardner, 1937). Patients with high thresholds caused by Menière's disease (Hallpike & Hood, 1959) or noise exposure (Ward, Fleer, & Glorig, 1961), both of which lead to damage of the hair cells, often report they are disturbed by loud sounds. Thus a person with a mid-frequency threshold at 60 dB SPL, 50 dB higher than normal, may call sounds at 90 dB SPL very loud, even annoyingly loud.

Quantitative measurements are usually obtained by loudness matches either between a good ear and a bad ear in cases of unilateral pathology (alternate binaural loudness balance) or between a tone at a frequency with an abnormal threshold and a tone in the same ear at a frequency with a normal threshold. Such tests are routine in many audiological clinics. Miskolczy-Fodor (1960) pooled 300 loudness matches by patients who showed loudness recruitment. In all the cases recruitment was complete, meaning that loudness eventually reached a normal level after starting from an elevated threshold. The data indicate that the greater the hearing loss, the steeper the loudness function. Stevens and Guirao (1967) have suggested that the data fit their power-transformation model. The data are too scattered to distinguish between a double power function and a smooth curve, but they do fit the model's prediction that the slope of the loudness function increases with threshold. The data also are similar to those collected from normal listeners for a partially masked tone.

Although loudness adaptation is absent in normal ears, might it occur in impaired ears? In certain types of deafness, usually involving lesion of the auditory nerve or more central parts of the auditory system, a tone not far above threshold soon becomes inaudible if left on continuously (Ward, 1973). Harbart, Weiss, and Wilpizeski (1968) could not find a corresponding decay of loudness at suprathreshold levels. Of course, a tone near threshold must decrease in loudness before it disappears, but at higher levels even severely impaired auditory systems do not show significant amounts of loudness adaptation.

In addition to loudness recruitment, listeners with severe cochlear impairment show no loudness summation over bandwidth. For such listeners, the loudness of four equally loud tones does not increase with Δ F or bandwidth even when the tones cover a frequency range much wider than the critical bandwidth (Scharf & Hellman, 1966). For normal listeners who heard the four tones against an intense masking noise, loudness summation was less than in the quiet but still measurable and as much as predicted by a model of loudness summation developed for normal ears (Zwicker & Scharf, 1965). These results suggested the possibility that the critical band is abnormally large in ears with a cochlear impairment. Also, despite the similarity of loudness recruitment in cochlear deafness and under masking, the underlying processes may be quite different in the two conditions.

Listeners with a conductive hearing loss show normal loudness summation. They also have normal loudness functions--no recruitment--an exception to the rule that loudness grows more rapidly from elevated thresholds than from normal, mid-frequency thresholds. This exception suggests that loudness recruitment occurs only when threshold is raised by changes beyond the middle ear such as occur in masking, fatigue, and cochlear impairment.

D. Individual Differences

Not all listeners with normal hearing exhibit loudness functions like the standard function (Figure 1). Some listeners do not give a good power function; more important, listeners give functions with different slopes. J. C. Stevens and Guirao (1964) measured functions for eleven listeners under a combined estimation-production procedure in which the subject both set the level of the stimulus and assigned a number proportional to its loudness. The exponents in the first session ranged from 0.4 to 1.1. Other investigators (deBarbenza, Bryan, & Tempest, 1970; McGill, 1960; Reason, 1968) have also found large individual differences in the slopes of loudness functions. (A steep loudness function from a normal listener may be distinguished from a steep function from a listener with impaired hearing not only because threshold is normal, but because the normal listener's function does not become flat at 30 or 40 dB SL.) Loudness functions probably differ among normal listeners for many and complex reasons, some of a stable nature and some less stable. Stable variations could include variations in the auditory system or less specifiable variations in personality. Non-stable variation could be random or accidental influences that affect judgments from one stimulus presentation to another and from one session to another. To a limited extent each of these possibilities has been treated experimentally.

Ross (1968a) showed that much of the variability among the equal-loudness contours measured on three subjects could be ascribed to differences in the impedance of the middle ear. However, since the impedance was independent of intensity below about 100 dB SPL, impedance differences could not account for possible differences in the slope of the loudness function. Slope differences are more likely to be based on variations in the cochlea. But Ross's analysis does point up the possibility of accounting for at least some of the variability in loudness judgments on the basis of specifiable and presumably stable physiological differences.

Stephens (1970) has reported some tentative conclusions based on magnitude estimations that link personality differences, as measured by a standard test of anxiety, with differences in the slope of the loudness function. High-anxiety scorers gave steeper loudness functions than did low-anxiety scorers. While highly tentative (mainly because the slopes did not correlate with four other measures of personality), these data suggest, quite reasonably, that different kinds of people use different strategies in estimating loudness, or any other subjective continuum. The question really is to what extent such "extraneous" factors as personality and experience with numbers affect loudness estimations.

J. C. Stevens and Guirao (1964) noted that their subjects gave a different exponent in a second session, one to six months after the first session. The correlation between the exponents from the first and second sessions was 0.53, which suggests that much of the difference among subjects in their judgment of loudness is not constant and stable but is unstable, perhaps random. This conclusion is reinforced by the finding that subjects gave power functions with quite different exponents when they judged visual area in two sessions eleven weeks apart (Teghtsoonian & Teghtsoonian, 1971). The obtained correlation between the individual slopes of the power functions in the first session and those in the second session was near zero. At least 90% of the variance in individual exponents was attributable to chance factors. Quite possibly the same is true for loudness functions.

Consequently, differences among the loudness functions from normal listeners are apparently not, for the most part, directly related to the ways the auditory system works. Therefore, pooling loudness judgments from a group of normal subjects is a suitable procedure for arriving at the best estimate of the slope of the loudness function. Personality and other such individual differences seem to account for little of the variance in loudness functions. To the extent that "central" factors affect loudness, it is wise to attempt to cancel them out by averaging across subjects.

VII. Physiological Correlates of Loudness

Auditory physiologists seldom look directly for physiological correlates of loudness; rather, they try to discover how the auditory system codes sound pressure. Physiological events that are monotonic functions of sound pressure give rise to a sequence of mechanical events in the middle ear and cochlea that culminate in the bending of the "hairs" of the hair cells. Just how the deformation of the hairs, which apparently triggers neural activity, varies with sound pressure is not known. It is known, however, that the maximum amplitude of displacement of the basilar membrane, on which the hair cells sit, is a linear or nearly linear function of sound pressure (just how linear is uncertain: see Johnstone and Yates, in press, and Rhode and Robles, in press). Consequently, up to the point of transduction, the major physiological correlate of loudness is amplitude of displacement.

Beyond transduction, the great unknown of all sensory physiology, what is the <u>neural</u> correlate of loudness? The classical answer has been the quantity of neural activity as measured by the number of nerve impulses per second (Davis, 1959). The more active the auditory nervous system, the greater the loudness. More activity is achieved by a higher <u>rate</u> of firing in single neurons and by a larger <u>number</u> of active units.

In all sensory modalities, neurons respond more rapidly to stronger stimuli. The auditory system, in addition, has more units active at higher stimulus intensities. A sound wave displaces the basilar membrane not at a single point but along much of its length, how much depends on sound pressure. Thus, with increasing pressure, both the depth and breadth of displacement increase; so too does the number of active fibers because the hair cells and their nerve fibers are distributed along the whole basilar membrane. The depth or amplitude of displacement determines how fast the neurons fire, and the breadth or extent of the displacement determines how many of them fire.

Widening the bandwidth of a sound, even without increasing overall intensity, broadens the area of displacement on the basilar membrane. Presumably that is why loudness increases with stimulus bandwidth. It is not known, however, why loudness does not begin to increase until bandwidth exceeds the critical band; perhaps, displacement only then begins to broaden.

Loudness depends on stimulus frequency as well as on bandwidth and sound pressure. At threshold, most of the variation with frequency disappears if relative amplitude of displacement on the basilar membrane is computed at each frequency instead of sound pressure level (Zwislocki, 1965). Differences in sensitivity arise largely from the frequency-dependent transmission of sound pressure through the peripheral auditory system to the hair cells. For the same reason, the equal-loudness contours are not flat over frequency. But below 1000 Hz, they are also not parallel to each other or to the threshold curve. They become flatter at higher levels, which means that loudness increases more rapidly with level at low frequencies than at middle or high frequencies. No doubt, they become flatter at higher intensities partly because the low-frequency internal noise, which raises the threshold for low-frequency tones, masks strong tones less effectively than weak tones. Another factor may be the rapid increase in the area of displacement on the basilar membrane as a low-frequency tone is intensified. With increasing level, the displacement pattern spreads mainly from the place of maximum displacement toward the stapes. Since a low-frequency sound produces a displacement pattern on the basilar membrane with a maximum toward the apical end, the pattern has plenty of room to spread out. (Partly to avoid this influence, Stevens, 1972, advocated using a reference sound located near 3000 Hz instead of a 1000-Hz tone.)

Much of the variance in loudness seems related to the displacement pattern on the basilar membrane. Loudness also depends, however, on time. Up to 100 msec or so, loudness increases with duration. Zwislocki (1969) suggests that this temporal summation occurs in some central part of the auditory nervous system. He ascribes the observed shortening of the time constant at suprathreshold levels to temporal decay of the neural firing rate at the input to an hypothesized integrator. An essential and almost unavoidable assumption is that the auditory system does not integrate acoustic energy but neural energy. For a change, the mechanical events in the cochlear are secondary.

The approach that equates loudness with the amount of neural activity usually ascribes the effects of masking, fatigue, and cochlear pathology to a reduction in the number of units available for responding to the test signal. But why is there a rapid increase in loudness once threshold is exceeded? One answer has been that inner hair cells first become active at high intensities, perhaps at 50 dB and higher; unaffected by the masking or fatiguing sound, they are able to respond as the signal increases above the masked or fatigued threshold (e.g. Simmons & Dixon, 1966). Becoming active, these cells signal high loudness levels. Recent data by Kiang (1968), however, fail to give evidence for high-threshold units in the peripheral auditory system.

Although intuitively appealing and supported by many data, the notion that loudness is a simple correlate of total neural activity may be wrong or, at best, incomplete. Kiang (1968) undermines the notion with data from the cat's auditory nerve. He notes that single units increase their firing rate in response to increased sound pressure over a maximum stimulus range of only 40 dB. Furthermore, those units sensitive to the same stimulus frequencies all begin to respond at about the same level of stimulation; the threshold range is little more than 20 or 30 dB. Kiang finds no evidence for a population of high-threshold units which could be served exclusively by the inner hair cells. How then can loudness increase from threshold to well over 120 dB SPL? The dynamic range of a single unit is at most 40 dB and the maximum difference in threshold between units is 30 dB, which together account for a range of only 70 dB. Can the spread of excitation to larger numbers of fibers account for the missing 60 or more dB? Perhaps, but how then does a low-frequency tone manage to increase in loudness in the presence of a high-pass noise (Hellman, 1973)? And what about white noise whose loudness also continues to grow over at least 120 dB? A white noise already stimulates the whole basilar membrane since it contains all the audible frequencies. As intensity increases, additional units can come in at low and high frequencies where thresholds are high. But by about 100 dB the equal-loud contours are nearly flat over much of the audible region; yet the loudness of white noise continues to increase above 100 dB. Loudness coding may involve more than simply the quantity of neural activity.

Despite these difficulties, some direct physiological measurements have shown that neural activity does continue to increase up to high sound pressure levels. Teas, Eldredge, and Davis (1962) found that the amplitude of the action potential, produced by the guinea pig's auditory nerve, grew with sound pressure from a level of 50 dB to over 100 dB. Moreover, the amplitude increased as a reasonably good power function of sound pressure (Stevens, 1970). Boudreau (1965) also measured power functions for the amplitude of the integrated neural response in the superior olivary complex, but the range over which the neural response increased seldom was as large as 60 dB. Evidence from other modalities suggests that the power function may be determined right at the sensory receptor where stimulus energy is transduced to neural energy (Stevens, 1970); just how the auditory system manages it is an intriguing question.

Other approaches to the problem of loudness coding are possible. For example, Luce and Green (1972) have presented a model of sensory magnitude based primarily upon the interval between "neural" pulses. The model accommodates a variety of data on discrimination, recognition, magnitude estimation, and reaction time with heavy emphasis on hearing. It works so nicely for a variety of psychophysical tasks that hopefully the model can be applied more generally to loudness and such critical variables as bandwidth, masking, and fatigue.

VIII. Models of Loudness

Investigators have long sought to calculate loudness from the physical characteristics of a sound. A system for calculating the loudness of a sound from its spectrum often entails a model that transforms acoustical parameters into quasi-physiological analogues. One of the earliest models was based on masking (Fletcher & Munson, 1937). The model had two basic principles: (1) the spread and amplitude of the excitation evoked by a sound in the auditory system can be approximated from the sound's masking pattern, i.e. the degree to which the sound completely masks pure tones over a wide range of frequencies; (2) loudness is directly related to this excitation. These principles reappear in the models of Harris (1959), Howes (1950), and Munson and Gardner (1950) and serve also in Zwicker's comprehensive model (Zwicker, 1958, 1963; Zwicker & Scharf, 1965). Other schemes for calculating loudness (Reichardt, Notbohm, & Jursch, 1969; Stevens, 1972) or its close relative, noisiness (Kryter, 1970), are designed primarily to yield the correct loudness estimate rather than model the auditory system.

Figure 11's top curve is an example of the kind of masking pattern used in Zwicker's model, a pattern obtained from the complete masking of pure tones by a narrow-band noise. Zwicker's model converts masking in decibels first to excitation and then to specific loudness, the loudness per critical band. Frequency on the abscissa is converted to tonalness, a scale based on critical bands and approximately proportional to distance along the basilar membrane. Specific loudness plotted against tonalness yields a loudness pattern, whose integral is the loudness of the narrow-band noise that was the original masker. The same loudness pattern serves for any subcritical sound, including a pure tone, with the same intensity and center frequency as the original noise. The same loudness pattern can be used for a whole set of subcritical bandwidths because equally intense sounds narrower than a given critical band are all equally loud (see Section III C).

Sounds wider than a critical band require broader excitation and loudness patterns. Each component critical band is then represented by its own excitation pattern. All the patterns are geometrically combined. Where patterns from different critical bands overlap, they are adjusted to take into account mutual inhibition which reduces the contribution from each component to the overall loudness. Despite this reduction, a broader pattern means greater loudness for supercritical sounds.

Zwicker's model also permits the calculation of loudness against a masking noise. Figure 12 shows how the model is applied to a tone masked by a narrow-band noise. (Data for such a combination are given in Figure 11.) The ideal spectra for the tone and noise are at the top of the figure. Below them are the theoretical excitation patterns, based on masking, which the tone and various levels of noise produce in the auditory system. To simplify the example in Figure 12, let us assume that whichever pattern has a higher excitation level completely suppresses the other at a given tonalness. Accordingly, the shaded portions of the tone's pattern contribute nothing to the loudness of the tone, which is calculated by converting excitation level to specific loudness and integrating.

Not only does the model provide a measure of loudness, but more important for present purposes, it illustrates probable interactions within the auditory system. For example, Figure 12 shows why one sound completely masks another

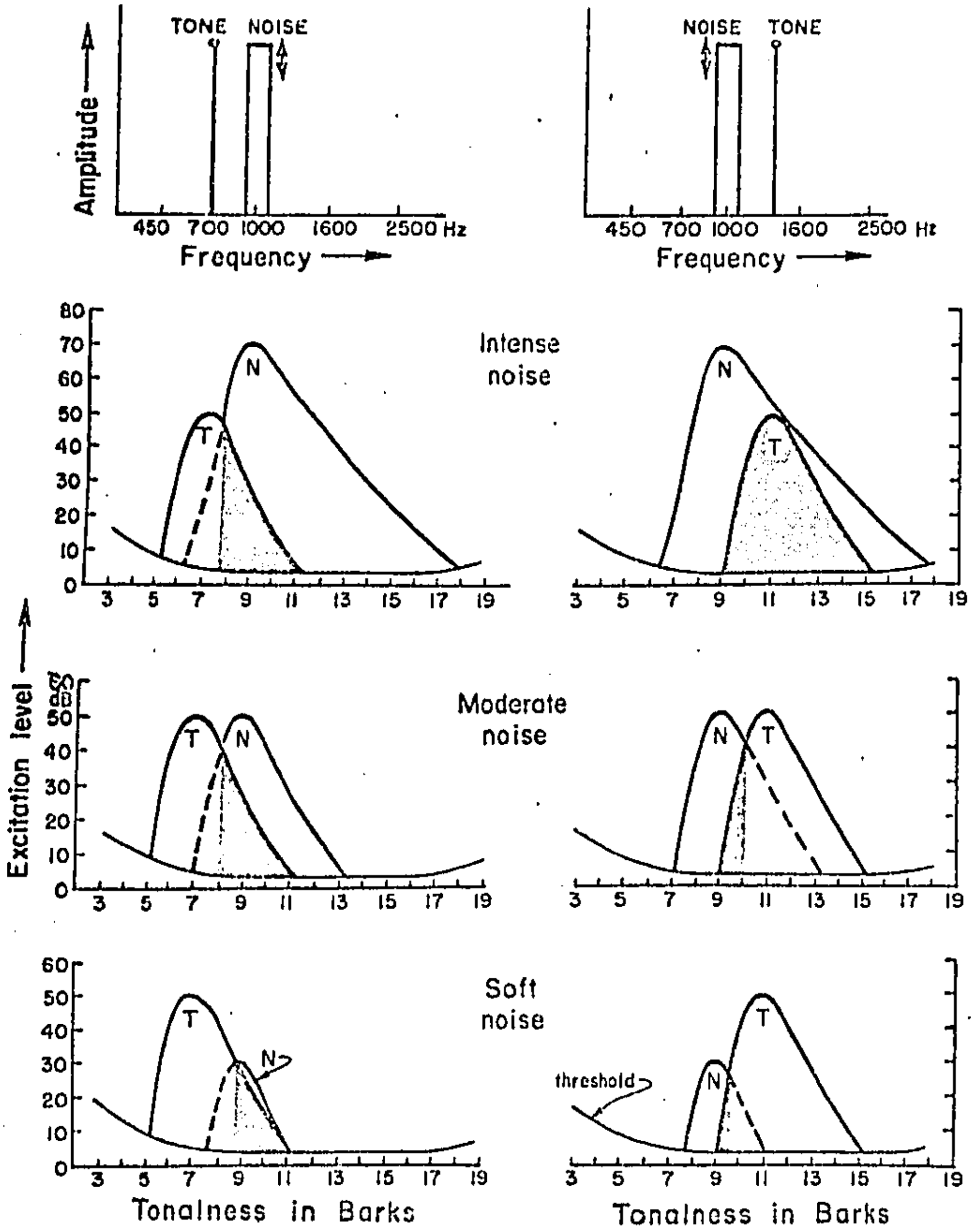

Fig. 12. Excitation patterns for a narrow-band noise and two pure tones. [Ideal spectra are shown at the top (Scharf, 1964, adapted with permission of Acustica).]

sound at a higher frequency more easily than a sound at a lower frequency. The pattern produced by the intense noise is skewed toward the higher frequencies, and completely envelopes the pattern produced by the higher-frequency tone, making it inaudible. The same noise pattern only partially covers the pattern of the lower-frequency tone, and so that tone is faint but easily heard. When the noise intensity is reduced, however, much of its pattern now lies under that of the higher-frequency tone, and so most of the tone's pattern is free to contribute to loudness. In contrast, a good part of the lower-frequency tone continues to be suppressed even by the soft noise. Thus, on the basis of the skewed masking patterns and the assumption that loudness is the integral of the whole excitation pattern, the model explains why the loudness of the higher-frequency tone grows very rapidly as the noise is softened (or if the tone is intensified and the noise held constant), while the loudness of the lower-frequency tone grows more slowly.

Other calculation schemes also take into account the mutual inhibition among the components of a wide-band sound, but they do not provide the geometrical picture that Zwicker does and that Fletcher and Munson did. If one's prime purpose is to compute loudness level, then Stevens's (1972) procedure is simpler to use and may be more accurate than Zwicker's, but if the prime purpose is to analyze possible interactions within the auditory system or to predict loudness under masking and for narrow-band signals, then Zwicker's system is better.

Except for a calculation system developed by Niese (1965; Reichardt, et al, 1969), none of the systems takes temporal summation into account. They are meant to apply to sounds that last longer than about 200 msec and that have no significant short-duration components. Uncertainties about the appropriate time constant is one reason for this omission.

At present Stevens's system is the United States standard for the calculation of the loudness of sounds (USA Standard, 1968), and both his method and Zwicker's are recommended by the International Standards Organization (ISO, 1966). Stevens (1972) has suggested some modifications of his procedure. In addition, Kryter's (1970) procedure is frequently used in the calculation of noisiness, an attribute often indistinguishable from loudness. The increasing concern with noise pollution may compel adoption of a single calculation scheme. Nonetheless, the various procedures provide results similar enough to permit reasonable decisions on the basis of any one of them.

IX. Meaning of Loudness

A. Loudness as Subjective Intensity

Loudness is the subjective intensity of a sound. Subjective means a sentient listener, human or animal, must respond to the sound. Intensity is normally a physical term, but the modifier "subjective" puts intensity in the observer and brings along all the other senses where subjective intensity seems to be part and parcel of every sensation. The many experiments in which subjects have successfully equated the intensity of one sensation to that of another--of loudness to brightness, force of handgrip to vibratory strength, loudness to roughness, etc. (Stevens, 1966)--show that subjective intensity is common to all the sensory modalities. Sound, in the definition, assigns loudness to hearing.

Any sound, even one as simple as a pure tone, is more than just louder or softer. People can respond to its pitch, size, density, duration, vocality, annoyingness. A complex sound such as a band of noise, a bird's song, a pile driver has still more attributes: meaning, timbre, roughness, intermittency, color. Telling a subject to judge loudness and ignore all other attributes of a sound leaves the experimenter who attempts to measure an equal-loudness contour or a loudness function at the mercy of the subject's interpretation of loudness (or intensity or strength).

Striving for a rigorous definition, Stevens (1934) proposed that a sensory attribute must have independent invariance. It must be possible to hold the given attribute constant while all other attributes vary. For example, Stevens told his subjects to make two tones of different frequency equal in loudness by adjusting the sound pressure of one of them. Presenting tones at different frequencies, Stevens mapped out an equal-loudness contour. He then told the subjects to make two tones of different frequency equal in density, or volume (size), or pitch--again by adjusting the intensity of one of the two tones. Figure 13 shows the four different equal-sensation contours these matches produced. Instructions to match for "brightness" or other possible attributes did not yield a fifth equal-sensation contour. Apparently, a pure tone manipulated as in these experiments has only four attributes, one of which is loudness. Note that varying two physical parameters of a sound, frequency and intensity, yields four sensory attributes. The equal-loudness contour is so labelled to correspond to the instructions given in that experiment.

Once established as an independent attribute, its functional relation to the relevant stimulus properties can be mapped out. That is what much of this chapter has been about. Loudness, as subjective intensity, is sometimes incorrectly identified with physical intensity, primarily because loudness is so closely associated with physical intensity, being a relatively simple, monotonic function of sound pressure. One could perhaps define loudness as the attribute of a sound that changes most readily when sound intensity is varied.

No matter how hard we try, we seem unable to measure loudness without using language. Somehow, the subject must be told to judge loudness by one means or another. The experimenter has no way of determining that a judgment is right or wrong; only the listener can say what the loudness ratio is between two sounds. The experimenter hopes that the subject chooses the right criteria. (The experimenter also hopes that the subject listens, not only to the instructions but to the stimuli. A subject may report a sound as much softer--even non-existent--when he pays no heed to it than when he listens carefully. In the laboratory, getting subjects to pay attention to the stimuli is seldom a problem, but in the real world of intrusive noise, attention and habituation are often critical variables.)

Stevens could label one of the equal-sensation contours of Figure 13 an equal-loudness contour, because loudness or some similar term was used in the instructions. Had the subject been an animal, trained to respond to equality, the problem would have been to get the animal to respond only on the basis of loudness. How do you train for loudness without knowing what makes different sounds equally loud? Unless you assume the animal's loudness contours are like human contours, an unfounded assumption that in any case returns you once again to verbally based judgments. Training and language

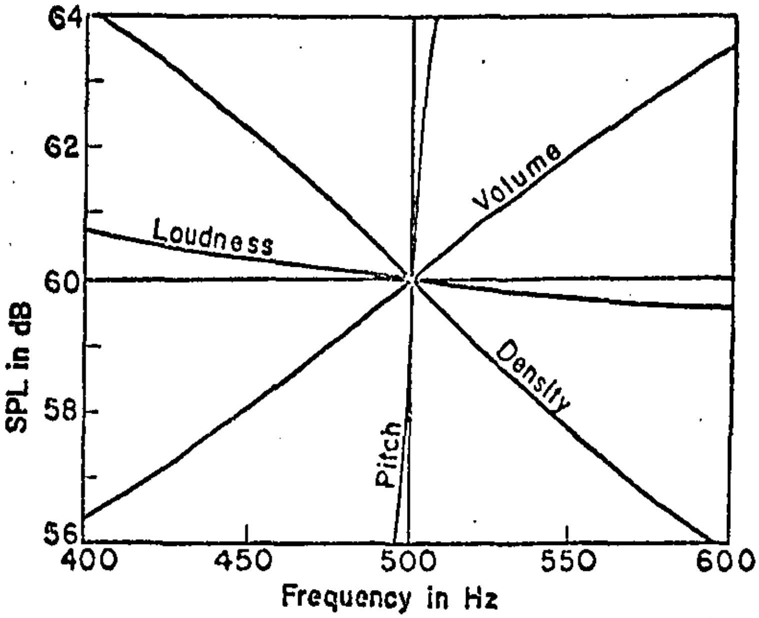

Fig. 13. Equal-sensation contours for pure tones. [The sound pressure level is shown to which a pure tone must be set in order to remain constant in loudness, volume, density, or pitch as its frequency is varied (Stevens, 1934).]

can be avoided with both human and animal subjects by measuring response latency or physiological changes that follow auditory stimulation. These nonverbal measures can be only indirectly related to loudness, and not always successfully, as we see in the next section.

B. Nonverbal Measures of Loudness

A sound evokes many kinds of responses, some voluntary, most involuntary. Only voluntary responses, often verbal and always under the control of verbal instructions, have provided data about loudness. Other kinds of responses, entirely nonverbal, must be used to study loudness in animals, very young children, severe retardates. The problem is to find nonverbal responses that are highly correlated with loudness. The search has concentrated on evoked potentials, a normally involuntary physiological change, and reaction time, one aspect of a normally voluntary behavioral response. These responses, like certain other electrical, muscular, and vascular changes, can be measured without disturbing the auditory system. Those physiological measures that require surgical intervention within the auditory nervous system are discussed in Section VII.

The nonverbal procedures, like the standard psychophysical procedures, are used to find out how the response depends on stimulus variables such as frequency, bandwidth, background noise; and observer variables such as pathology and noise exposure. First, we look at measurements of reaction time in humans and animals, and then measurements of involuntary, physiological changes.

1. Reaction Time

Chocholle (1940) pioneered in showing how the time it takes to react to a sound depends on intensity and frequency. The subject's task was to press a telegraph key as soon as he heard the sound. The data established two important facts. Reaction times to equally loud sounds are equal; and the louder the sound, the shorter the reaction time. Thus, tones at very different frequencies and sensation levels but at the same loudness levels yielded the same reaction times. Chocholle (1954) could represent a subject's reaction times to frequencies ranging from 50 Hz to 10,000 Hz by a single curve, which is reproduced in Figure 14. Reaction time stopped decreasing at loudness levels above 80 or 90 phons, no doubt owing to a lower limit of the order of 100 msec for human motor responses. These same data could be used to estimate equal loudness among different frequencies. The derived equal-loudness contours resemble those Fletcher and Munson (1933) obtained by loudness matching (see Figure 3).

If non-sensory factors place a lower limit on auditory reaction time, then subtracting 100 msec from the measured values ought to provide a better estimate of the sensory component and its functional relation to sound intensity. Thus "corrected," reaction time is a good power function of loudness level between 20 and 90 phons. Below 20 phons the function steepens. The slope of the power function, however, is only about 0.2, much lower than the 0.6 of the standard loudness function. Such a low exponent means not only that reaction time changes with level much more slowly than does loudness, but also that it would be difficult to determine whether a power function, a logarithmic function, or some other function best fits the data.

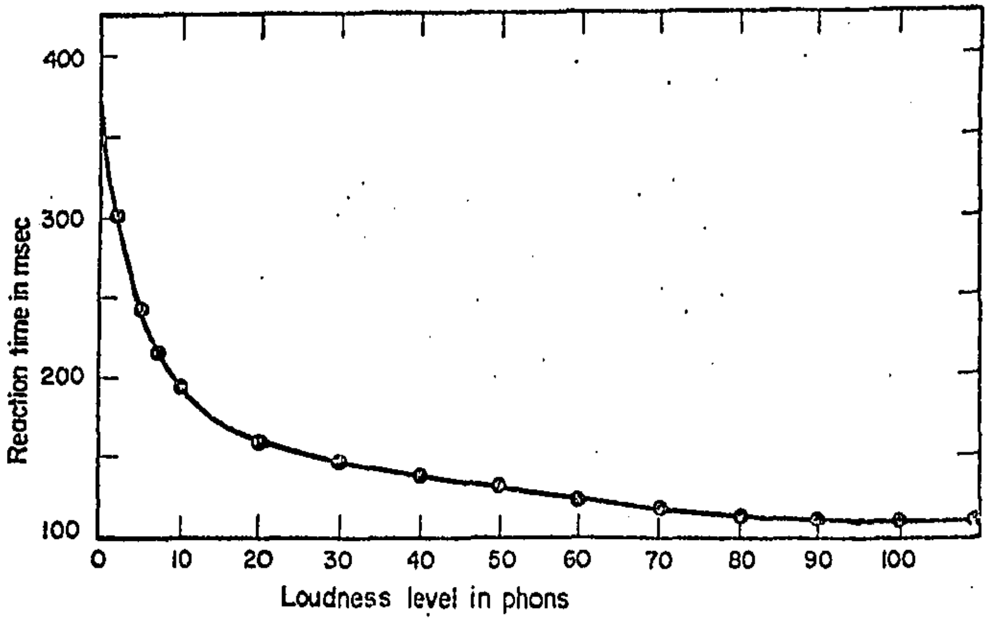

Fig. 14. A single listener's reaction time to a pure tone as a function of loudness level. [The same curve represents tones varying in frequency from 50 to 10,000 Hz (Chocholle, 1954, adapted with permission of Annales d'Oto-Laryngologie, published by Masson & Cie., Paris).]

Whatever their precise relation, so long as reaction time is a simple monotonic function of level, loudness and reaction time can be simply related. For example, if reaction time is a power function of sound pressure with an exponent of 0.2 then reaction time is a power function of loudness with an exponent of 0.33. A crucial question is whether a similar transform works when the slope of the loudness function is altered by background noise, cochlear pathology, noise exposure, etc. Reaction time, like loudness, does change faster with signal level in the presence of a partially masking sound than in the quiet, but the precise relation between reaction-time functions and loudness functions under masking seems not to have been determined (Chocholle & Da Costa, 1971; Chocholle & Greenbaum, 1966). Similarly, it would be interesting to compare the binaural-to-monaural loudness ratio to the binaural-to-monaural reaction-time ratio, measured in the same experiment. Binaural reaction times are faster (Chocholle, 1946). [It is rather puzzling that whereas reaction time to sound fails to match loudness functions, reaction time to light appears to duplicate human brightness functions very well (Mansfield, in press).]

The reaction times of animals to sound also depends in a lawful manner on stimulus parameters. Stebbins (1966; Stebbins & Lanson, 1961) has trained monkeys to depress a bar upon the onset of a warning signal and then release it as soon as the auditory signal comes on. The monkey's reaction time or response latency is over twice as long as a well-trained human's, but it changes with intensity in similar fashion, decreasing rapidly at near-threshold levels and much more slowly at higher levels. Variability in the monkey is not much greater than the average standard deviation of 10% for man reported by Chocholle (1954). Moody (1970; in press) has uncovered another similarity. After exposure to a loud tone, monkeys have longer latencies to tones near the elevated threshold, but with increasing intensity, the latency quickly becomes normal. This rapid drop in latency can be identified with loudness recruitment similar to that measured in humans after exposure to intense sounds (see Section VI B).

Response latency to tones of different frequency has been used to construct the monkey's equal-latency contours. The contours are not the same as equal-loudness contours for man (see Figures 3 and 4)--partly because the monkey can hear much higher frequencies, up to 45 kHz--but they are similar enough to support the assumption that equal response latency means equal loudness.

2. Involuntary, Physiological Responses

Among the many involuntary responses elicited by a sound are the electrical changes in the nervous system observable most readily as evoked potentials on the scalp. Much attention has also been given to the acoustic reflex, the contraction of the stapedial muscle in response to intense sounds.

The brain produces so much electrical activity, that a change evoked by a sound can be recognized only by averaging over the time-locked responses to many repetitions of the same sound. The averaged wave form bares recognizable features that correlate with various stimulus parameters. The amplitude of the evoked potential is commonly measured, although latency may sometimes provide relevant information.

Keidel and Spreng (1965) found that the amplitude of a slow component of the evoked potential increases as a power function of sound pressure. The exponent was smaller than the standard 0.6 but how much smaller was not reported (the authors gave only the exponent multiplied by an unstated factor). Davis and Zerlin (1965) also measured a power function with a small exponent, 0.24. Davis, Bowers, and Hirsh (1968) measured a still smaller exponent for a 1000-Hz tone, 0.11. Since the data both between and within subjects were highly variable, power functions with such small exponents are not easily distinguished from linear, logarithmic, or other functions. However, Davis et al. (1968) did find that the cortical potential grows much more rapidly from a masked threshold in the presence of a band of noise than in the quiet. The steep rise resembles loudness recruitment. Despite this resemblance, Davis (in press), in an overview of the relation between cortical potentials and sensation magnitude, stresses the great variability in evoked potentials and reports a poor correlation between loudness and the amplitude of the evoked potential.

Although poorly correlated with the loudness function, evoked potentials do seem to have roughly the same amplitude when stimuli are equally loud. Tones different in frequency and level but equal in loudness evoke similar cortical potentials (Davis et al., 1968; Davis & Zerlin, 1965; Keidel & Spreng, 1965). Equally loud binaural and monaural signals also evoke equal potentials, but if equally intense, then the louder binaural signal evokes a larger potential (Allen, 1968; Davis & Zerlin, 1965). In general, the corollary of the rule that equal loudness evokes equal potentials is valid, i.e., louder signals evoke bigger potentials. Accordingly, potentials grow not only with signal intensity, but also with signal duration up to 100 to 200 msec (Spreng, 1967) and bandwidth (Davis et al., 1968; Spreng, 1967). [Davis and Zerlin (1965), however, did not find a change in the evoked potential with increasing signal duration.]

With respect to loudness, evoked potentials and reaction times bare some striking similarities. Both change more slowly than loudness as a function of sound pressure, both may be power functions of sound pressure, and each is roughly invariant for equally loud sounds. It remains to compare evoked potentials and reaction times to each other in the same experiment with the same listeners.

The evoked potential reflects gross activity in unspecifiable parts of the brain. Potentials from the human auditory nerve have also been measured by inserting an electrode through the back wall of the ear canal to bring it close to the ear drum (Saloman & Elberling, 1971) or inserting it right through the ear drum (Aran, Portmann, Portmann, & Pelerin, 1972; Yoshie & Ohashi, 1969). As the intensity of a click stimulus increases, the amplitude of selected components of the auditory potential goes up and their latency goes down. These techniques, being developed primarily in the clinic, have revealed recruitment of the nerve response in some patients who have cochlear impairment with evidence of loudness recruitment. Perhaps, data will become available to indicate the extent to which the shape and slope of the loudness function are determined at the transducer.

A different approach to the measurement of auditory responses involves the acoustic reflex. An intense sound causes the stapedial muscle to contract, resulting in a change in the impedance of the middle ear. The amount of change has been measured as a function of sound pressure, frequency, and bandwidth (Hung & Dallos, 1972). Measurements have been restricted to levels above 70 dB SPL; at lower levels, the reflex is too weak, if present at all, to measure. Nevertheless, the acoustic reflex has been shown to reflect the relation between loudness and frequency (Ross, 1968b), between loudness and bandwidth--but with a much wider "critical band"--(Flottorp, Djupesland, & Winther, 1971), between loudness and intensity in cochlear pathology (Ewertsen, Filling, Terkildsen, & Thomsen, 1958), and between binaural loudness and monaural loudness (Simmons, 1965).

Few reports on physiological responses to sound seem to concern responses outside the auditory system. Epstein and Eldot (1972) and Sokolov (1968) measured changes in skin resistance, which became larger as sound intensity increased, and Epstein and Eldot also observed, using a classical conditioning procedure, more rapid changes with level under masking than in the quiet. Sokolov and Vinograd (1968) measured changes in the volume blood flow in the vessels of the head and hand as a function of sensation level.

All the various nonverbal responses to sound are clearly and meaningfully related to many of the same stimulus and observer variables that determine loudness. Some measures, notably the cortical evoked potential and reaction time, seem to be invariant when loudness is constant. None seems to correlate very well with loudness ratios, and so leaves unfulfilled the hope of finding "objective" validation for the loudness function.

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FOOTNOTES

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1. We owe the origin of the concept of loudness level and its unit, the phon, to the German acoustician Barkhausen (1926).

2. A value of 4.5×10^{-4} for P_0 yields a fair approximation of the modified power function in Figure 1. The equation then reads

$$L = 10.45 \, (P - 4.5 \times 10^{-4})^{.6}$$

where L is loudness in sones and P is sound pressure measured in dynes per cm^2. The chosen value for P_0 corresponds to a loudness level of 7 phons, only 1 phon above our assumed detection threshold.

3. Why is not a steeper loudness function accompanied by smaller ΔIs? One possible reason is that a steeper function means that any variation in the stimulus or its transmission through the ear (and possibly in transduction) are magnified within the auditory nervous system. Consequently, the variance of the distribution of events elicited in the sensory domain by a signal at a given level is increased where the loudness function is steeper. Since discrimination requires distinguishing between two distributions of sensory events to which two stimuli may give rise, any increase in the variance of those distributions must lead to reduced discrimination. However, the whole relation between discrimination and sensory-magnitude functions is unclear, but is coming under closer scrutiny (see e.g. Teghtsoonian, 1971).

4. These statements assume that transitivity holds for loudness matches, i.e., that if sounds A and B are equal in loudness to sound C, say a 1000-Hz tone, at a given level, then sound A is equal in loudness to sound B. Robinson and Dadson (1956) and Ross (1967) have shown experimentally that transitivity holds within the limits of variability of loudness matches between tones of different frequency.