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On the Effect of Noise of Fluctuating Levels

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On the effect of noise of fluctuating levels

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Introduction

Information in the form of sound waves is communicated as functions of frequency, intensity and time. In order to grasp these processes we must employ a three-dimensional representation.

In a piece of orchestral music we regard the concerted playing and its changes from pianissimo to fortissimo as a pleasing sensation. The cumulative effect of machine and industrial noise, which may coincide with that of a piece of music, is found to be unpleasant, annoying and damaging.

The preceding papers have considered the damaging effects of noise which lead to deafness. The importance of frequency and its representation by the A weighted network and by limit curves, e.g. n.r. curves has also been treated.

In this paper I shall limit myself to the relation between the sound-pressure level in dB(A) and the duration and effect of noise on the human being.

An attempt is made to calculate numerically the disturbance to human beings caused by noise of varying amplitudes and durational characteristics. The shorter the duration of the sound in the course of the working day, the higher the level which can be allowed. If we assume that an equal amount of sound energy results in an equal degree of annoyance, then when the duration is reduced to a half, a level of noise higher than for $q = 3$ could be tolerated.

Equivalent steady level

In order to obtain the so-called steady level $L_{\text{eq.}}$ we arrive at the numerical correspondence given by equation (1*a*):

$$\left.\begin{aligned} L_{\text{eq.}} &= 10\log_{10}\left(\frac{1}{T}\sum_i 10^{0\cdot 1L_i}t_i\right) \quad (a)\\ &= 10\log_{10}\left(\frac{1}{TI_0}\sum_i I_i t_i\right) \quad \text{dB}(b)\end{aligned}\right\}. \tag{1}$$

Here L_i is the steady level during the time t_i. The summation is to be applied for the total time T. By replacing the level L_i by the corresponding intensity I_i we arrive at equation (1*b*).

The assumption of dependence upon sound energy alone (i.e. $q = 3$) is a supposition which can be modified to any chosen figure for q greater or less than 3. In the general case equation (2) applies:

$$L_{\text{eq.}} = 10\,(q/3)\,\log_{10}\left(\frac{1}{T}\sum_i 10^{0\cdot 1L_i(3/q)}t_i\right) = 10\,(q/3)\,\log_{10}\left(\frac{1}{TI_0^{3/q}}\sum_i I_i^{3/q}t_i\right)\text{dB}. \tag{2}$$

One must substitute for the power function I_i the expression $I_i^{3/q}$ (3 represents approximately the ratio of the logarithms to the bases 2 and 10).

In figure 1 $L_{max.}$ is effective for a duration t_h and is higher than the lowest level by $\Delta L = 10$ dB. The ratio of the time t_h of $L_{max.}$ to the total time $t_{tot,}$ is plotted as the abscissa. The curves with $q = 1$ to $q = 6$ show the increase of the equivalent level over the lowest level $L_{min.}$. The greater q is, the smaller the increase. With $L_{max.}$ acting for one-tenth of the total time the curve for $q = 3$ only reaches 3 dB.

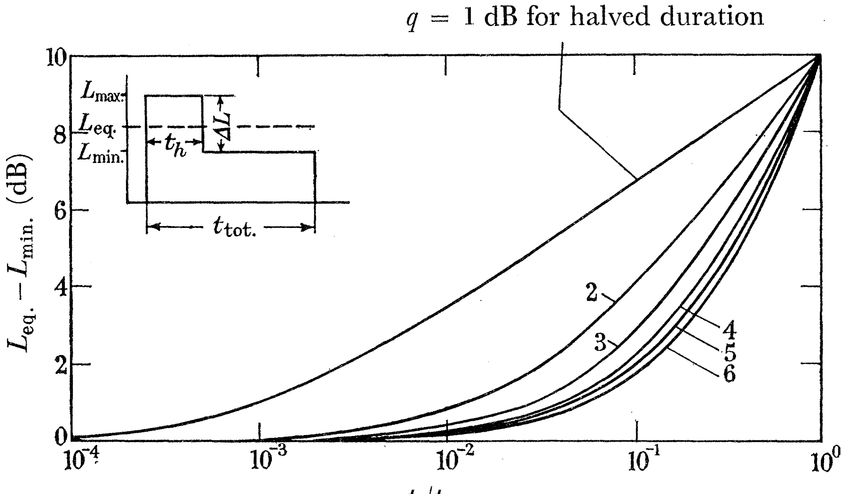

FIGURE 1. Dependence of the equivalent steady sound level $L_{eq.}$ relative to minimum level $L_{min.}$ for different duration ratios $t_h/t_{tot.}$ with q (dB) for halved duration as parameter $\Delta L = 10$ dB.

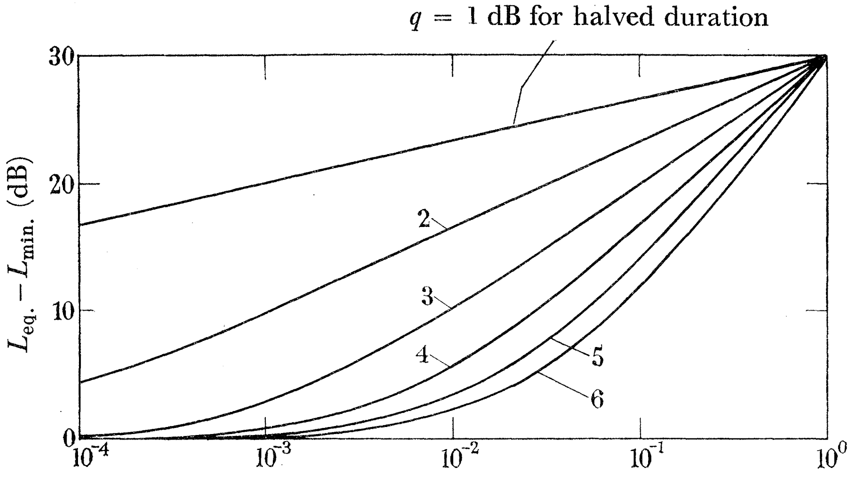

FIGURE 2. Dependence of the equivalent steady sound level $L_{eq.}$ relative to minimum level $\Delta L = 30$ dB.

If $\Delta L = 30$ dB (figure 2) the increase of $L_{min.}$ is noticeably greater. And when the duration of $L_{max.}$ is only 1/1000 of the total time, the increase to $q = 3$ remains 3 dB.

Figure 3 shows for $q = 3$ by how many decibels $L_{eq.}$ is less than the $L_{max.}$ level. The abscissa ΔL indicates by how many decibels the lowest level is exceeded. The curves are plotted for a series of values of the ratio of the effective time t_h to the total time $t_{tot.}$. The oblique line shows the coincidence of $L_{eq.}$ with $L_{min.}$. With the high noise occupying 10 % of the time (48 min in 8 h) differential levels ΔL greater than 20 dB reduce the effective noise level by not more than 10 dB; with 1 % of the time (that is 4·8 min in 8 h) differentials of over 30 dB reduce the effective loudness by not more than 20 dB, and with 0·1 % (that is 28 s in 8 h) by not more than 30 dB for ΔL greater than 40 dB.

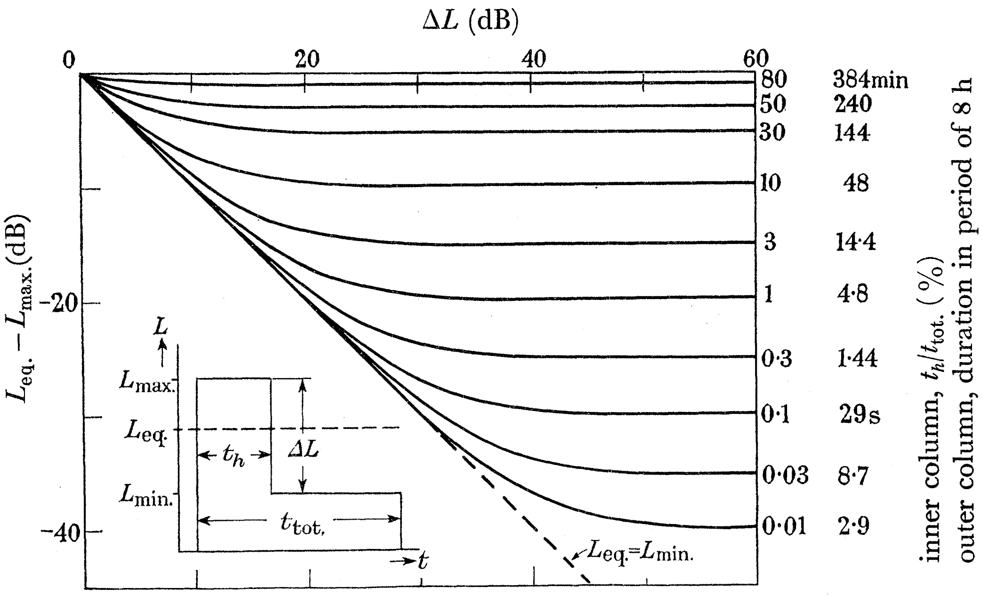

FIGURE 3. Difference between maximum sound level $L_{max.}$ and equivalent level $L_{eq.}$ dependent on the level difference $L_{max.} - L_{min.}$ and on the duration ratio ($q = 3$).

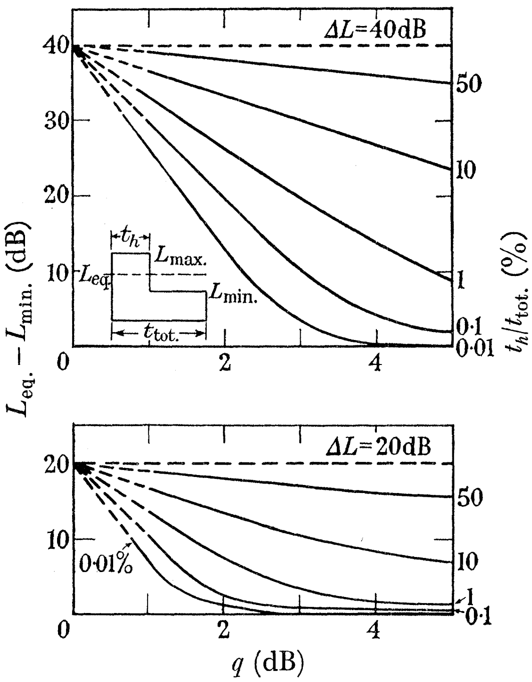

FIGURE 4. Difference between equivalent level $L_{eq.}$ and lower level $L_{min.}$ plotted against q for several fractions $t_h/t_{tot.}$.

The influence that the value q can have on the decrease of $L_{eq.}$ with a level difference of ΔL equal to 40 and 20 dB respectively for the various time ratios is shown in figure 4. The greater q is, and the smaller the ratio of t_h to $t_{tot.}$ is, the less $L_{eq.}$ will be over $L_{min.}$.

The relation illustrated in the previous figures are likewise valid for the following noise and number indices, n.n.i. (Wilson Committee 1963) applying to the evaluation of aircraft noise and the equivalent German (Koppe, Matschat & Müller 1965/66) unit $\overline{Q}$. In an attempt to achieve an approximation of the actual noise evaluation, $q = 4$ and $q = 4{\cdot}5$ respectively have been selected in this presentation. That means that the actual relatively brief burst over $L_{\text{min.}}$ increases the level only slightly.

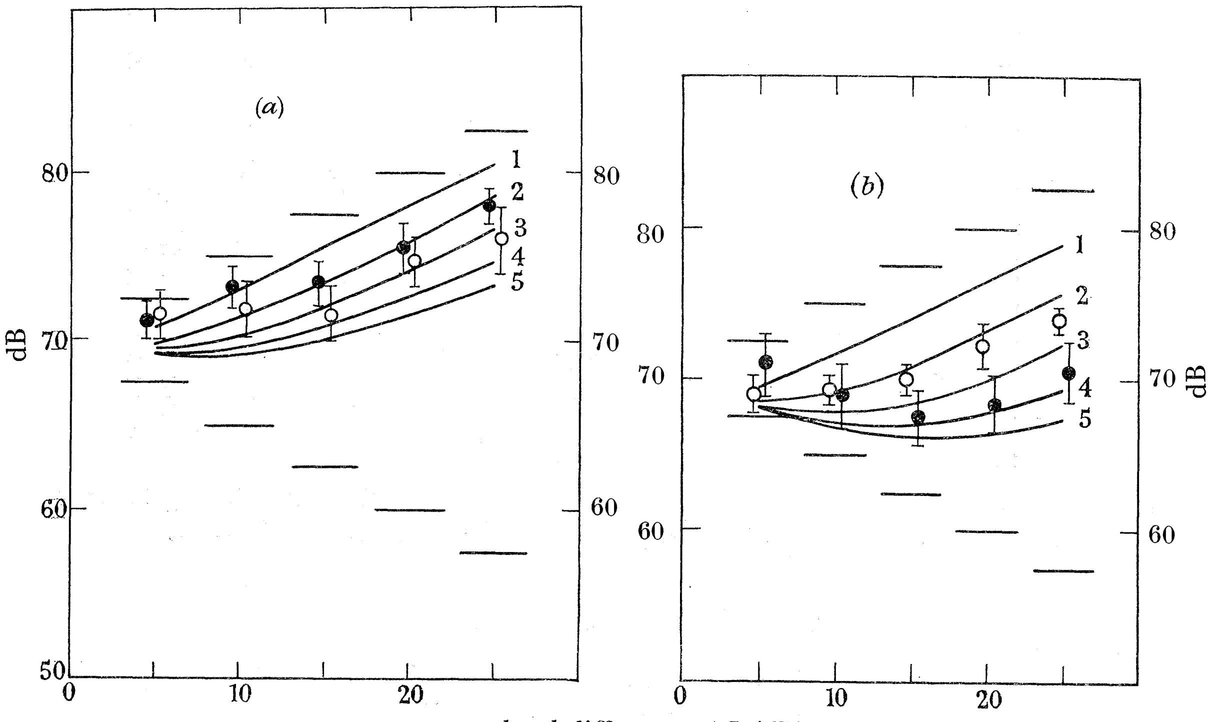

Figure 5. Comparison of calculated equivalent steady level (curves numbered with their respective q-value) with subjectively found levels (mean values with confidence interval for 95 %). ●, Noise of $\frac{1}{3}$ octave band 1 kHz; ○, sinusoidal tone 1 kHz. Duration ratio: (*a*) 0·3; (*b*) 0·1. $L_{\text{max.}}$ and $L_{\text{min.}}$ are indicated by horizontal bars.

In the calculation of the equivalent levels from the individual levels exceeding $L_{\text{min.}}$, an exact knowledge of q is necessary. Experimentally it is only possible to determine it for a relatively short time, i.e. the total time can only be extended up to 30 s (Lübcke & Gummlich 1966; Lübcke, Gummlich & Mittag 1966). With the rare occurrence of bursts within a period of minutes or even hours, the hearing mechanism (resulting from a lack of acoustic memory) loses the ability of registering the annoyance of bursts in the way that a steady level would be registered.

Measured values of q

We have conducted research into the question of 'equally annoying' as opposed to the usual question 'equally loud', by the use of listening-comparison tests. Figure 5*a* shows measured values arrived at subjectively in which, starting from a mean level of 70 dB, the maxima were increased and the minima decreased by the same quantity. In this way level differentials of between 5 and 25 dB resulted such that, for 0·3 of the total time

(20 to 25 s) the maximum exceeded $L_{min.}$ by 5 to 25 dB. As standard sound, a tone and a $\frac{1}{3}$ octave-band noise centred on 1 kHz medium frequency was used; 95 % of all measured values lay within the designated area. It can be seen that the noise values are higher than those of the 1 kHz tone and that the scatter for the noise is less. Also indicated are theoretical curves calculated for the duration ratio 0·3 for $q = 1$ to $q = 5$ It can be seen that the measured values are distributed about a curve slightly above the theoretical curve for $q = 3$.

In figure 5 *b* can be seen the results for the same ΔL, but for a duration ratio of 0·1. One can see that here for the tone of 1 kHz (marked by a black point), q of about 4 could be considered, while for the $\frac{1}{3}$ octave-band noise a $q \sim 3$ seems to fit. Whereas in the previous figure the points almost follow the maximal values, here they are in the middle between maximum and minimum as expected. The measuring points also follow the pattern of the curvature so that, for these periodic oscillations between maximum and minimum in a total time of an order of magnitude of 10 to 30 s, there appears to be no contradictions for the supposition concerning the q values. Unfortunately we cannot supply reproducible values for longer durations.

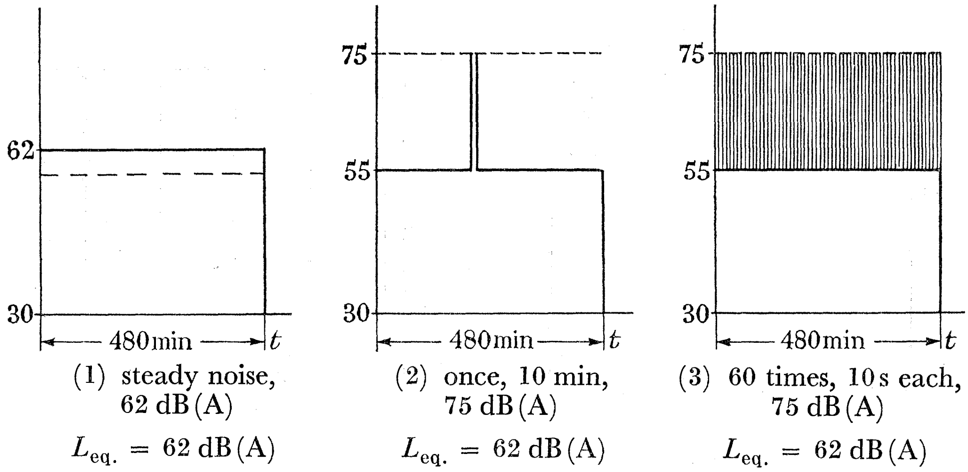

FIGURE 6. Three noises with the same equivalent steady-sound level $L_{eq.} = 62$ dB (A) and different annoyance. $q = 2·5$.

ADDITION AND SUBDIVISION OF SEVERAL DURATIONS OF EQUAL-SOUND PRESSURE LEVEL

Prerequisite for the calculation of the equivalent steady level is that one can add sound levels of equal intensity but of differing durations to the total. When one takes into consideration the differing annoyance effects produced by each of these bursts, one should consider the greater annoyance qualities of many short bursts of noise.

This may be illustrated by figure 6. A steady noise of 55 dB (A) during the 480 min of the work shift, is overloaded for 10 min with a high level of 75 dB (A) as a result of which the equivalent level is increased to 62 dB (A). The same increase occurs when, now on the right side, the high level of 75 dB (A) follows not once during the shift but rather 60 times for about 10 s duration each time. This noise pattern is undoubtedly more annoying than the steady level of 62 dB (A) indicated on the left side.

It is probably unwise to assume constancy of q for all time ratios of $t_h/t_{tot.}$ and for all level differences $L_{max.}$ to $L_{min.}$. The shorter the time ratio, the greater the q must be selected. This would similarly apply to the increasing of the level difference.

Example for the influence of q

Two examples can be chosen to illustrate the influence the selection of q has on the equivalent levels.

We take two industrial areas (figure 7), A and B. In A, $L_{min.}$ is 50 dB (A) resulting from loud industrial activity. In the quiet area B it is only 30 dB (A). In each area the sound level may be increased by aircraft noise to 70 dB (A) five times for a length of 1 min each during the shift of 8 h. Thus we have in area A an equivalent sound level $L_{eq.}$ of 55 dB (A); in the other area, B, we have an almost identical equivalent steady level of 54 dB (A). In case A, the level difference is 20 dB (A) and the equivalent level $L_{eq.}$ is only 5 dB (A) over $L_{min.}$. In case B, $\Delta L = 40$ dB for 1 % of the total time; therefore if $q = 2{\cdot}5$ the increase for the entire shift duration is a considerable one of 24 dB (A) and the noise level increases from $L_{min.} = 30$ dB (A) to $L_{eq.} = 57$ dB(A).

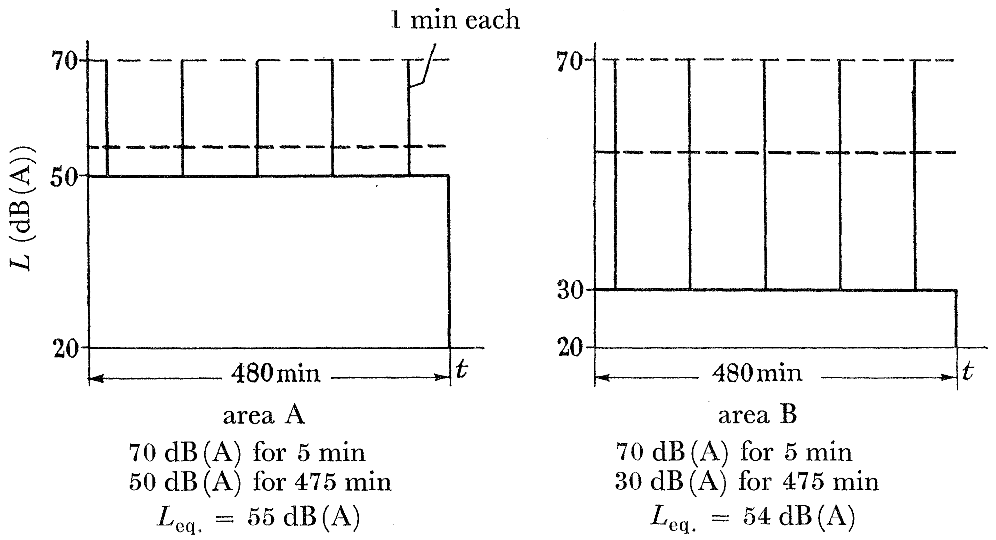

Figure 7. Calculated $L_{eq.}$ in areas with different background level and the same high level by $q = 2{\cdot}5$.

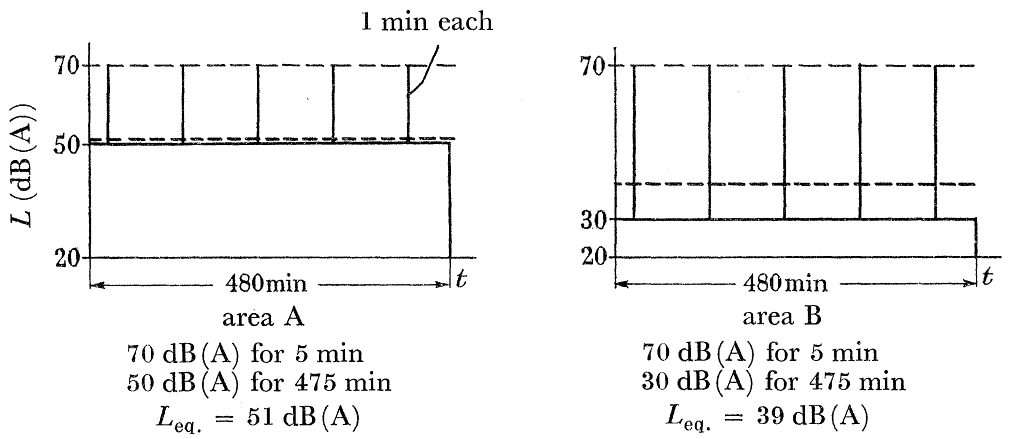

Figure 8. Calculated $L_{eq.}$ and the same conditions as in figure 7, but with $q = 5$.

If a q twice as large is selected (figure 8), namely $q = 5$, then in area A the equivalent sound level will only be increased 1 dB over $L_{min.}$, to 51 dB (A), and is thus imperceptible. In area B the ΔL of 40 dB for 5 min during the shift introduces an equivalent level of $L_{eq.} = 39$ dB (A). This seems reasonable. It is clear that uncertainty still exists and that exact regulations for this sort of calculation of equivalent sound levels may be premature: how reliable is the distribution of duration of time into small portions? And: to what degree is q dependent on the time ratio and the sound level difference?

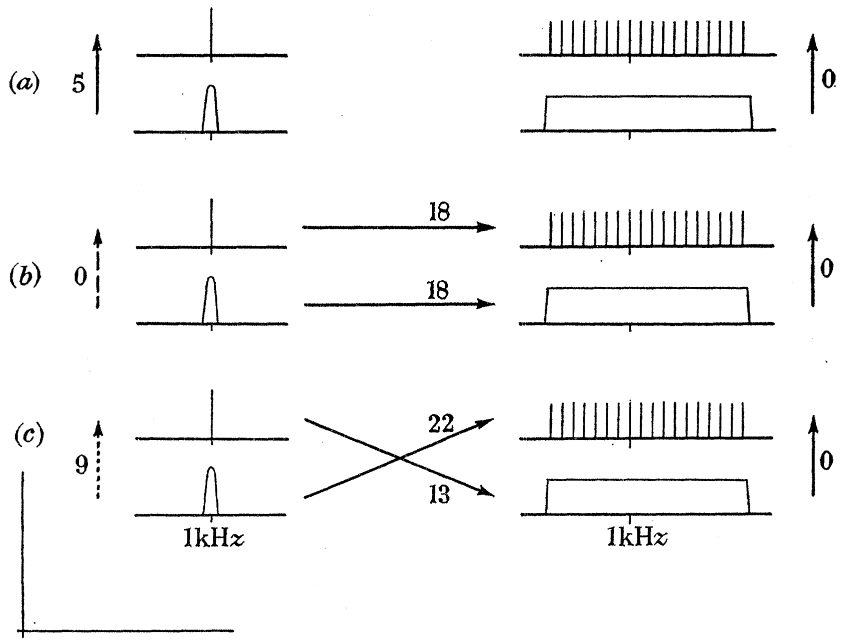

FIGURE 9. Subjective comparison of several sounds with the same level but with different component in equal frequency range. Figures in phons as differences of loudness levels, $L \sim 55$ dB.

LOUDNESS MEASUREMENTS OF DIFFERENTLY COMPOSED SOUNDS

There is an apparent paradox in the measurement of loudness by hearing comparisons. Suppose we have four different sounds (figure 9). Two noises are composed of pure tones, one a standard tone of 1 kHz and one a broad-band noise, constructed of 21 tones, each one in the middle of a critical band (freqüenzgrüppe) according to Zwicker (1961). Of the two others, one is a white noise from a critical band around 1 kHz, the other is an evenly stimulating noise of a bandwidth equal to that of the 21 tones.

If we compare both these standard noises at equal sound levels with each other, they are not equally loud; rather the 1 kHz tone is 5 phons louder than the critical band noise (figure 9*a*) (full arrow 5 left).

If we compare the two broad-band noises as object noises with each other, there is no difference in the loudness levels of the two (figure 9*a*) (full arrow 0 right).

If the standard tone of 1 kHz is measured against the one broadband noise composed of 21 tones, there is a sound-level difference of 18 phons (figure 9*b*) (top horizontal arrow 18).

The same difference of 18 phons results by the comparison of the critical-band noise with the broad-band noise (figure 9*b*) (bottom horizontal arrow 18).

If one now cross-measures the 21-tone noise with the critical-band noise, then there exists a difference of 22 phons (figure 9*c*); if the broad-band noise is cross-measured with the 1 kHz tone, a difference of 13 phons is found.

That means, therefore, that the total difference between both sequences of comparison yields 9 phons whereas it should be 0 (indicated by the broken arrows at the left of figure 9*b* as 0 and of figure 9*c* as 9).

The mode of composition of the broad-band noise must be considered when we compare the same noise with either a tone or a critical-band noise. But if one compares the two broad-band noises of different composition with each other, the loudness levels are equal. This presents a paradox with needs further explanation.

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