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Loudness of tone pulses in a free field

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Investigations of temporal loudness summation of tone pulses have been performed. The investigations comprised equal loudness determinations between pairs of tone pulses with a duration ratio of 1:2, and threshold determinations of the same tone pulses. Pulse durations ranged from 5 to 640 ms. The frequencies were 500, 1000, and 4000 Hz. All pulses were shaped by means of 1/3 octave filters. For 25 normal hearing observers the investigations were performed at the observer's threshold, and at 35 and 55 dB SPL. Fitting of the experimental data to a single exponential function yields a time constant (τ) of about 200 ms near and at the threshold, whereas τ is about 100 ms at levels well above threshold. Discrepancies exist, nevertheless, between this single-time-constant model and the experimental data obtained for the pulses of shortest duration. To account for this, a model is proposed comprising a combination of two exponential functions. This yields a short time constant of 5 to 10 ms combined with the longer time constant mentioned above.

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I. INTRODUCTION

For brief sound stimuli the loudness depends very strongly on the duration of the stimuli. After the onset of a steplike stimulus the loudness will grow and after some time (less than 1 s) reach a steady value. This phenomenon is called temporal integration or temporal loudness summation.

For many years research has been carried out in order to determine the relationship between the duration of the stimulus and auditory perception. The investigations may be divided into two groups:

(a) Threshold measurements performed either at the quiet or at a masked threshold, e.g., Garner and Miller (1947), Feldtkeller and Oetinger (1956), Plomp and Bouman (1959), Hempstock *et al.* (1964), Pedersen and Elberling (1972), Năbělek (1978).

(b) Loudness balances and magnitude estimations performed at levels above threshold, e.g., Niese (1959), Port (1959), Zwicker (1966), Stevens and Hall (1966), Boone (1973), McFadden (1975).

This paper deals with temporal integration in a free field at threshold and at suprathreshold levels, evaluation of the description of the temporal integration by means of a time constant, and a model comprising two time constants.

A. Models

The time constant description of temporal integration is given by the relation

$$I_t/I_\infty = 1/(1 - e^{-t/\tau}). \tag{1}$$

The left side is the ratio between the intensities necessary to reach threshold—or to obtain equal loudness—for a pulse of duration t, and for a long lasting pulse. The time constant is τ. For $t \ll \tau$ Eq. (1) predicts that loudness can be maintained if a halving of the duration is compensated for by a doubling of the intensity, thus keeping the energy constant.

In the present investigation tone pulses of short duration are matched in loudness to pulses of double duration. The ratio between the two intensities at equal loudness is found by using Eq. (1) twice and eliminating I_∞:

$$I_t/I_{2t} = 1 + e^{-t/\tau}. \tag{2}$$

For $t \ll \tau$ this ratio is almost equal to 2. This means that a level difference of 3 dB must be expected for very short pulse durations.

Zwislocki's (1960) theory of temporal integration led to a time constant model. At the threshold of audibility, the time constant was found to be on the order of 200 ms. Above threshold the effective time constant decreased to about 100 ms (Zwislocki, 1969). The theory takes both psychophysical and neurophysiological factors into account. Especially the effect of the temporal decay of the neural firing rate makes it possible for the model to describe a variety of experimental data. For references and descriptions of other models see, e.g., Năbělek (1978), Penner (1978), Ehret (1976), and Irwin and Kemp (1976).

II. METHOD

The measurements were performed at threshold and at 35 and 55 dB SPL, using 1000-Hz tone pulses. For the two levels above threshold 500- and 4000-Hz tone pulses were also used. Combined with the levels from the international Round Robin Test on impulsive noise (Pedersen *et al.*, 1977) the range was extended up to 95 dB SPL for 1000-Hz tone pulses.

Apart from the threshold measurements all the measurements were performed as loundness balances between tone pulses of different durations. The signals were presented in pairs via a loudspeaker in an anechoic chamber. One of the two signals in the pair always had a duration twice the other. Thus a 20-ms pulse was compared in loudness with a 40-ms pulse, a 40-ms with an 80-ms pulse, etc. This method reduces the difficulties for the observer and hence the variance in the results as pulses having this duration ratio sound more alike than pulses deviating very much in duration (Niese, 1956).

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A. Apparatus

The observers were seated in an anechoic chamber approximately 2 m from an electrostatic loudspeaker, QUAD. The tone pulses were generated by a programmable function generator, Wavetek 155, which was controlled by a PDP 8 minicomputer. The pulses were filtered in a $\frac{1}{3}$-octave filter, Brüel & Kjær 1615. Their level was set by a computer-controlled Hewlett-Packard 350 D attenuator.

B. Signals

Pulse durations were 5, 10, 20, 40, 80, 160, 320, and 640 ms. The pulses were generated from pure tones of 500, 1000, and 4000 Hz. (A 5-ms duration was not used with the 500-Hz tone pulses, because they would have been too close to threshold for some listeners.) One-third octave filtering avoided clicks and kept the bandwidth within approximately one critical band.

In order to keep the energy content of the filtered pulse at the same level as for the unfiltered pulse, small corrections are necessary. The corrections were found by direct measurement (squaring and integration) and were, for 1000-Hz tone pulses, 0.6 dB at 5 ms and 0.2 dB at 10 ms. For longer durations the corrections were smaller. Corrections are included in the data presented here.

C. Psychophysical method

The two pulses in each pair were compared in loudness. The second pulse always had half the duration of the first one and was presented 500 ms after the end of the first pulse. After a pause of 2.5 s the same pair was presented again. This sequence was repeated until the observer gave one of three responses: (1) first pulse louder than second pulse, (2) equally loud, (3) second pulse louder than first pulse. The responses were given by means of push buttons and registered by the computer. After each response a pause of 10 s was inserted; the pulse pair was presented again, with the level of the second pulse changed. The computer was programmed to work in accordance with the Method of Maximum Likelihood (MML), (Lyregaard and Pedersen, 1971, 1974). This is a bias-free adaptive method where the most likely psychometric function is estimated after each new response from the observer. The presentation levels are chosen in order to obtain maximum efficiency by avoiding redundant presentations. Due to randomination it is impossible—for the observer as well as for the investigator—to predict the course of the presentation levels. When the investigator sees that the estimation of the psychometric function has been stable during several responses, he stops the measurement. The results of a single loudness balance are typically based on about 20 evaluations.

It is assumed that the dependence of loudness on duration can be determined from loudness balances between tone pulses of 5 and 10, 10 and 20, 20 and 40, 40 and 80, 80 and 160, 160 and 320, and 320 and 640 ms. These balances were performed in a random order.

For the threshold measurements the MML procedure was slightly modified. The tone pulse was presented up to 5 times in a row at 500-ms intervals. The observer pressed a button as soon as he heard the pulse; the computer generated—after 2 s—a "not heard" response if the observer had not pressed the button. The observer did not know in advance when the pulses were presented.

D. Observers

Twenty-five observers were paid to participate in the measurements. They were male students between 17 and 22 years old from the Technical University of Denmark. Hearing thresholds were within 10 dB of normal (ISO 389), except that a hearing loss of 15 dB at a single frequency was allowed. For 1000 Hz only 10 dB was allowed. In some measurement series only some of the observers participated (see Table I).

III. RESULTS

Figure 1 shows the results for 1000-Hz tone pulses, and Fig. 2 shows the results for 500- and 4000-Hz tone pulses. As a function of pulse duration, the figures show equal loudness curves at different levels. The results at 1000 and 4000 Hz are quite similar, whereas the results at 500 Hz differ somewhat from the others at the 35-dB level.

Figure 3 shows data from the loudness balances at 1000 Hz, 35 dB SPL. Each data point shows the level difference necessary to obtain equal loudness for the

TABLE I. Estimated time constants yielding best fit by the method of least squares. Model comprising a single time constant (left) and model comprising two time constants (right). The fit may be evaluated by the sum of squared deviations, SSD.

Frequency	Level	No. of	Single time constant		Two time constants		
Hz	dB SPL	observers	τ, ms	SSD, dB^2	τ_1, ms	τ_2, ms	SSD, dB^2
500	35	12	110	2.2	...	...	...
500	55	12	50	2.6	...	...	...
1000	threshold	25	220	3.3	4	210	1.6
1000	35	11	320	10.3	14	280	0.3
1000	55	11	110	2.6	4	100	1.3
4000	35	9	240	6.4	8	220	0.9
4000	55	12	100	2.5	4	100	0.7

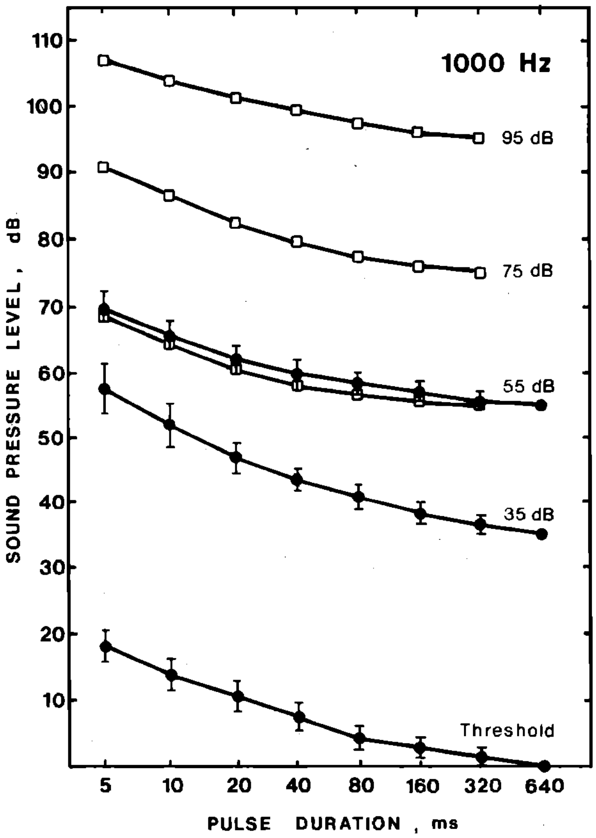

FIG. 1. Temporal integration of 1000-Hz tone pulses. Level is parameter. Filled circles are from the present investigation. Open squares are from the international Round Robin Test on impulsive noise. 95% confidence intervals are shown.

two pulses in a pair. The solid curve is the theoretical exponential function with a time constant of approximately $\tau = 300$ ms [Eq. (2)], and the asymptotic value of 3 dB (constant energy principle) is easily recognized. The "correct" time constant is found by shifting this

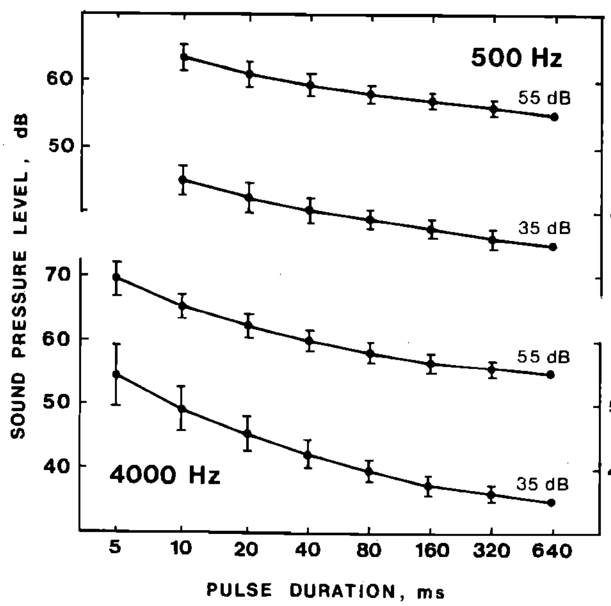

FIG. 2. Temporal integration of 500-Hz tone pulses (upper curves) and of 4000-Hz tone pulses (lower curves). 95% confidence intervals are shown.

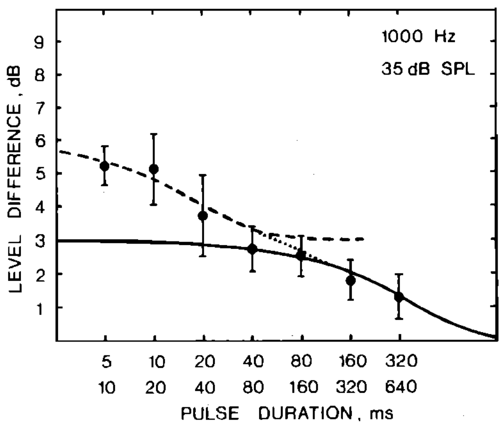

FIG. 3. Loudness balance of tone pulses having a duration ratio of 1 : 2. (By accumulating these data the 35-dB curve in Fig. 1 is achieved.) Solid curve shows an exponential model with a time constant $\tau \simeq 300$ ms. For the shortest pulses the data exceeds 3 dB resulting in a slope of the integration curve steeper than −3 dB per doubling of duration. If a short-time constant (dashed) is combined with a long-time constant (solid) the data exceeding 3 dB may be described. The combined model is shown dotted in the midrange.

curve along the abscissa until the best fit between curve and data is obtained. It is evident that no matter how much the curve is shifted along the abscissa the data for the shortest durations will never be reached as they exceed 3 dB. Despite these limitations in the fitting, time constants have been estimated (method of least squares) and are shown in Table I. In order to illustrate the discrepancies between the data points and the theoretical exponential curve, the sum of squared deviations (SSD) is also given. The data in the time constant estimation were mean values over subjects.

Since a better fitting is achieved by increasing the number of parameters in the model, two time constants are proposed. The expression is given in Eq. (3).

$$I_t/I_{2t} = (1 + e^{-t/\tau_1})(1 + e^{-t/\tau_2}) . \qquad (3)$$

The additional time constant in this model is schematically shown by the dashed curve in Fig. 3. The time constants obtained by means of this double exponential function are also shown in Table I. As the 5-ms pulse was omitted at 500 Hz the estimation of the short-time constant is of no significance at this frequency. By comparing the SSD's given in Table I it is seen that a much better description is achieved by a model comprising two time constants.

IV. DISCUSSION

For the 1000-Hz tone pulses it is possible to compare the data obtained in the ISO Round Robin Test on impulsive noise (Pedersen *et al.*, 1977). In that investigation approximately 300 observers distributed over 21 laboratories from all over the world participated. The aim was to find objective methods for measuring the loudness level of impulsive sounds, which would correlate well with subjective measurements. Besides loudness measurements of impulsive sounds in daily life, loudness balances of the same filtered 1000-Hz

TABLE II. As Table I, but data from international Round Robin Test on impulsive noise.

Frequency Hz	Level dB SPL	Single time constant τ, ms	SSD, dB^2	Two time constants τ_1, ms	τ_2, ms	SSD, dB^2
1000	55	80	6.4	10	50	0.6
1000	75	120	6.2	8	90	0.4
1000	95	80	0.8	2	80	0.6

tone pulses, as reported here, were performed at 55, 75, and 95 dB SPL. The results are shown in Fig. 1 by the unfilled squares. The curves obtained at 55 dB in the Round Robin Test and in the present investigation are in good agreement. Table II shows—for the Round Robin Test data—the estimated time constant in a single-constant model. It is seen that only at the highest level (95 dB SPL) is this model able to describe the data reasonably well. Fitting the same data to a model with two time constants yields the results also shown in Table II. At 55 and 75 dB, the reduction in the sum of squared deviations is considerable.

The threshold data are in good agreement with previous data (e.g., Hempstock *et al.*, 1964; Pedersen and Elberling, 1972). For 1000 Hz the time constant is 220 ms at threshold (single-constant model, Table I), whereas it is 110 ms at 55 dB SPL. The time constants are close to those from Zwislocki's model (1960, 1969). (Threshold measurements were not performed for 500 and 4000 Hz, but the time constant did tend to decrease at higher levels.)

A discrepancy is often found between the values predicted by the single-time-constant model and the experimental data at the shortest pulse durations, below 20 to 30 ms. For these short pulses the slope of the curve is steeper than -3 dB per doubling of duration. To overcomes this problem, Watson and Gengel (1969) took only three durations (32, 64, and 128 ms) into account when they computed the time constant, whereas Plomp and Bouman (1959) suggested a frequency-dependent correction to the model. The data reported here suggest level differences between 0 and 2 dB at durations longer than 40 ms, and between 2 and 5 dB at durations shorter than 40 ms. Accordingly, the model with two time constants was developed to permit a slope steeper than -3 dB per doubling of duration for the shortest pulses.

This model qualitatively separates the time domain into three intervals: durations shorter than τ_1, durations between τ_1 and τ_2, and durations longer than τ_2. This separation into time intervals is qualitatively in accordance with Zwicker (1973, 1974). He finds three characteristic durations in the hearing mechanism: 2, 20, and 200 ms. His results are based on different experiments which are not solely concerned with temporal integration. Zwicker states that the three values are valid for the hearing mechanism as such, but that the values may deviate by a factor of 2 towards larger or smaller values is quite possible.

Green *et al.* (1957) suggested that the temporal integration curve could be approximated by three intersecting lines with different slopes. At that time the increased slope (-4.5 dB per doubling of duration) used for pulse durations shorter than 15 ms was acribed to the increased bandwidth of these short pulses. Owing to the filter used in all the present measurements this spectral explanation is not valid here. For practical purposes, the very simple approximation by means of three straight lines could, on the other hand, yield an adequate description of the integration curve.

Baru (1971) has investigated the tone-pulse thresholds of dogs. Removal of the auditory cortex increases the threshold for pulse durations less than approximately 20 ms. Partly based on these results, he suggests that the hearing mechanism has a short time constant of 20 to 40 ms and a long constant of 100 to 200 ms.

V. CONCLUSION

From the results reported here it must be concluded that the single time-constant model cannot describe the experimental data adequately. This is mainly because level differences greater than 3 dB per doubling of duration are found for the shortest pulses (less than 20 to 40 ms), and thus the slope is steeper than predicted by the time-constant model. A model comprising a combination of two time constants is, on the other hand, able to reproduce the steeper slope of the curve at short durations. The short-time constant is 5 to 10 ms whereas the long-time constant is about 200 ms near threshold and about 100 ms at levels well above threshold.

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