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A CONTRIBUTION TO THE DETERMINATION OF THE FREQUENCY DISCRIMINATION ABILITY

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The *DL*'s for frequency as a function of the interstimulus intervals are experimentally determined. It is shown that the difference limens for frequency for both non-stationary and stationary signals clearly depend on the duration of the interstimulus interval up to the value ~ 256 ms. Moreover, it is shown that the recently published values of difference limen for frequency can be analytically expressed as the product of an exponential function and a resonance one where frequency and signal duration are parameters.

1. Introduction

In spite of intensive investigations the functional dependence of the difference limen for frequency (*DLf*) on various physical parameters (intensity, duration, frequency, etc.) of accoustical signals are determined unsatisfactorily. This regards mainly the influence of the interstimulus interval on the *DLf*. It is well-known that the interstimulus interval (*ISI*) between the constant and comparative acoustical signals is one of the physical parameters which affects the pitch perception and the discrimination ability of the auditory system. The values of the ISI are (published in works dealing with the determination of the auditory discrimination ability) different and their choice has an intuitive character. However, there are some experiments performed, aimed at finding the influence of *ISI* on the perception of stationary acoustical signals. KRÚTEL' [1] investigated the dependence of the difference limen for intensity *DLI* on *ISI* and showed its influence on the values of *DLI*. HARRIS [2] and KÖNING [3] found the influence of *ISI* on *DLf* as well. HARRIS did not find any expressive changes in *DLf* on *ISI* from the interval 0.3–3.5 s. KÖNING determined the influence of *ISI* on the frequency discrimination ability of stationary signals by means of five psychometric methods. The frequency of signals he used was 1000 Hz and the loudness level was 40 dB. He changed *ISI* in the range 0.31–5 s. Five subjects participated in these experiments. KÖNING found out that the frequency discrimination ability falls only weakly with increasing *ISI*, irrespective of the psychometric method.

As we note, *ISI* had relatively large values in the experiments of HARRIS and KÖNING. It seems to us, it would be convenient to investigate the influence of *ISI* on *DLf* for the smaller values and for non-stationary signals too. In what follows we present the results of such experiments.

Several papers (see for example [4]–[8]) have dealt with the determination of difference limens for frequency where the found values of *DLf* are fitted with some functions. Unfortunately, these functions express the dependence of *DLf* on one physical parameter only. Usually, this parameter is duration or frequency. In the present paper, a function of two parameters is shown, with which one can describe the dependence of *DLf* on duration and frequency as well. This function was found for the values of *DLf* published in [4, 5].

2. Experiments

We measured the dependence of *DLf* on *ISI* for acoustical signals, with the following values of *ISI*: 0, 16, 32, 64, 128, 256 and 1024 ms. The signal duration T was 32, 64, 128, 256 ms and the frequency $f = 1000$ Hz. The experiments were performed with stimuli whose loudness level for stationary signals was 60 dB. The envelope of the signals was a rectangular one and the initial phase was zero.

The method of constant stimuli was used. The value of *DLf*, assuming Gaussian distribution of subjects' answers was determined as a 50 percent level of the required sort of answers. The experiments were carried out monaurally and individually with four subjects. Two of them had no experience in psychoacoustical experiments. The subjects were situated in anechoic chamber. The subject's answer, (whether the presented stimuli were perceived as equal or non-equal) followed the presented stimuli and only then the next pair of stimuli was presented. Each subject gave 120 answers on the presented stimuli in one experiment. The frequency of the comparative stimulus was higher or at least equal to the frequency of the constant stimulus in the whole experiment.

A schematic diagram of the apparatus used is shown in Fig. 1. The standard stimulus and the comparative one came from generators of the sinusoidal

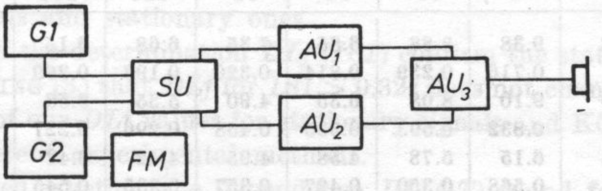

Fig. 1. A schematic diagram of the apparatus used. *G*1 and *G*2 are generators of sinusoidal signals, *FM* is the frequency meter, *SU* is the switching unit, *P* is the phone and AU_1, AU_2, AU_3 are the attenuation units, respectively

signals *G*1 (Brüel and Kjaer 1020) and *G*2 (Tesla BM 524), respectively. The frequency meter *FM* (Tesla BM 455 E) was permanently connected with *G*2 for control reasons. Signals from *G*1 and *G*2 were conducted to the switching unit *SU* (the laboratory product of the Institute of Physics SASc). It was possible to start the pairs of signals manully or automatically with a repeating period from the range 1–10 s. The signal duration *T* and interstimulus interval *ISI* were chosen in the *SU* from the range 0–1000 ms and 0–1500 ms, respectively. Then the signals from the *SU* were conducted through the attenuation units AU_1, AU_2, AU_3 (RFT Xa 716) which served for adjusting the required loudness level in the phone *P* (Melodium, Audio 15). The apparatus without the phone was located outside the anechoic chamber.

3. Results and discussion

The experimentally determined values of *DLf* (*ISI*) defined as an arithmetic mean of the frequency difference limens of the individual subjects, together with their standard deviations, are shown in Table and Figs. 2, 3. The significance of the deviation of the *DLf* values for the individual subjects from the arithmetic means was examined by a statistical *t*-test. The deviations were not significant at the 0.05 significance level and so we can consider them as random ones. By means of the *t*-test we also tested whether the change of the *DLf* value caused by the change of the interstimulus interval *ISI* is random or significant. It was shown for all signal durations T that the differences between *DLf* (*ISI* = = 0 ms) and *DLf* (*ISI* = 16 ms) are nonsignificant at the 0.05 significance level. Thus, it can be stated that not the presence of *ISI*, but its magnitude is decisive for the determination of *DLf*.

Table. *DLf* (*ISI*) as a function of the signal duration *T* for accoustical signals with a frequency of 1000 Hz. The upper values are *DLf*, the lower ones are the corresponding standard deviations (both are given in Hz)

T [ms]	*ISI* [ms]						
	0	16	32	64	128	256	1024
32	9.38	8.88	6.85	7.35	6.68	6.15	6.05
	0.716	0.239	0.814	0.320	0.193	0.269	0.265
64	9.10	8.08	6.35	4.90	5.35	3.58	3.48
	0.832	0.593	0.335	0.458	0.296	0.227	0.177
128	6.15	5.78	4.58	4.95	4.42	3.42	3.52
	0.568	0.350	0.427	0.357	0.335	0.545	0.150
256	5.92	5.52	4.45	4.42	3.42	2.98	3.12
	0.243	0.335	0.269	0.042	0.180	0.357	0.286

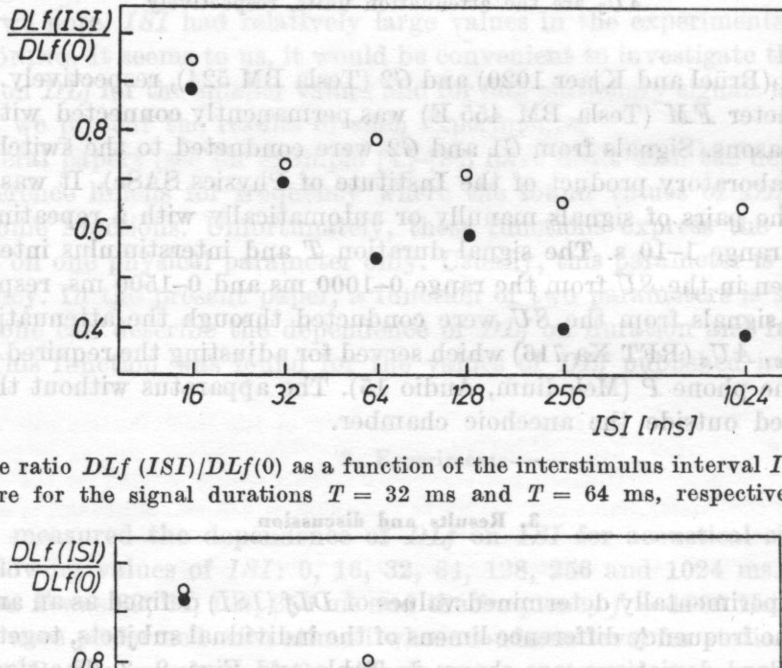

Fig. 2. The ratio *DLf* (*ISI*)/*DLf*(0) as a function of the interstimulus interval *ISI*. ○ and ● are for the signal durations $T = 32$ ms and $T = 64$ ms, respectively

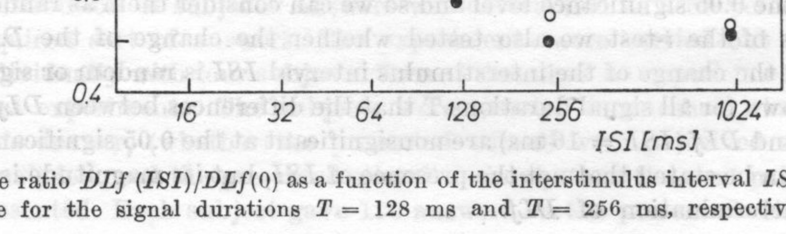

Fig. 3. The ratio *DLf* (*ISI*)/*DLf*(0) as a function of the interstimulus interval *ISI*. ○ and. ● are for the signal durations $T = 128$ ms and $T = 256$ ms, respectively

The values of *DLf* clearly decrease if *ISI* increases within the interval 16–32 ms. This kind of the dependence is broken off for non-stationary signals of durations, approximately, $T = 32$, 64 ms when $ISI \approx T$ and then continues up to the value $ISI \approx 256$ ms. *DLf* decreases if *ISI* increases for the stationary signal durations $T = 128$, 256 ms. The frequency discrimination ability does not change if *ISI* is approximately equal or more than 256 ms for both non-stationary signals and stationary ones.

Our results of the determination *DLf* (*ISI*) confirm the statements of HARRIS [2] and KÖNING [3] that *DLf* for $ISI > 0.32$s does not change significantly. The differences of our *DLf* values for stationary signals and KÖNING's ones are due to the different experimental methods.

We also tested whether the dependence *DL f*(*T*) found for *ISI* = const. agrees with the quantitative relationship

$$DLf = A + B/n + (B/n)^C, \tag{1}$$

determined in papers [4, 5] where n is the number of periods of the signal and A, B, C are constants. We showed that our results fulfil this equation but the constants A, B, C are other than in papers [4, 5] for a signal frequency of 1000 Hz. The agreement in the qualitative relationship may be considered as a certain criterium of the confidence of the results achieved. The differences in A, B, C are probably caused by the differences in the performance of the experiments.

In order to explain the dependences plotted in Figs. 2, 3 we assume that the values of *DLf* for short *ISI* are affected by the perstimulating and the poststimulating fatigue. When $ISI \to 0$ the masking phenomenon must be considered between standard stimulus and the comparative one. The poststimulating fatigue is manifested by an increase in the perception threshold during the short time till the full stimulation sensibility of the auditory system is restored. The interval of less sensibility depends on the intensity of the presented signals and differs for individual subjects. Adaptation phenomena can be explained by means of actions which are running in the peripheral auditory organ when the weak stimuli are presented. In the case of strong stimuli the adaptation phenomena in the brain might also cause the decrease of the sensibility of the competent analyzing elements.

4. The analytical expression of *DL f*(*f*, *T*)

Many authors interested in the investigation of the dependence of the frequency discrimination ability on the auditory system attempted to express analytically the empirical results. OETINGER [6] succeded in the determination of *DLf* as an analytical function of duration T of the signal in a short interval of duration. The results of LIANG CHIAN and ČISTOVIČ [7] can be also expressed through an analytical function of the form

$$\Delta z = \frac{\Delta z_0}{1-\exp(-T/T_0)},$$

where Δz_0 and T_0 are constants [8], if the frequency is recalculated in pitch (mels). Δz is the differences limen for pitch.

The analytical form of the curve of $DLf(T)$ for the most important range of frequency (from the point of view of the transfer information ability) of non-stationary signals was obtained by means of numerical calculations in papers [4, 5]. In these papers it has been shown that if the signal duration is expressed as a number of periods n, the function which fits best the empirical dependence DLf on n has the form of (1). The constants A, B, C are dependent on the signal frequency f. Equation (1) expresses one form of the auditory uncertainty relation [5].

It was shown that the experimental data of DLf from papers [4, 5] can be also expressed by the exponential function

$$DLf(f) = a\exp(bf), \tag{2}$$

where a, b are constants for a given frequency. The calculations showed that the values of b were constant ($b = 4\times10^{-4}\text{Hz}^{-1}$) and a was a function of the signal duration T. The function $a(T)$ is a decreasing one. The most suitable form of $a(T)$ from all types of functions which were investigated is

$$a(T) = K_1 + \frac{K_2}{(K_3+T)^2}, \tag{3}$$

where K_1, K_2, K_3 are constants. The most suitable values of K_1, K_2, K_3 and thereby the dependence $a(T)$ were found by means of the iteration procedure. By putting (3) into (2) one can obtain the following determination of $DLf(T,f)$:

$$DLf(T,f) = \left\{K_1 + \frac{K_2}{(K_3+T)^2}\right\}\exp(bf), \tag{4}$$

where $K_1 = 1.85$ Hz, $K_2 = 625.5$ s, $K_3 = 1.42$ s, $b = 4\times10^{-1}\text{Hz}^{-1}$.

The analytical expression (4) of the frequency discrimination ability describes empirical dependence sufficiently precisely mainly for signals of frequencies up to 4 kHz. The new analytical expression (4) of the function $DLf(T,f)$ is suitable mainly for the calculation of some information-theoretical parameters of the auditory system e.g. information content of acoustical signals as a function of duration and frequency [9].

5. Conclusion

From what has been said so far, it follows that:

1) *DLf* for signals of 1000 Hz frequency and durations from 32 ms up to 256 ms represents a function of the interstimulus interval *ISI*.

2) *DLf* reaches its maximum value if *ISI* is equal to zero. If *ISI* increases up to ~256 ms the *DLf* decreases. For $ISI > 256$ ms *DLf* is practically constant.

3) *DLf* can be expressed in a wide range of signal durations as a product of an exponential function and a resonance one.

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