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ON THE EAR'S DISCRIMINATING ABILITY DURING PHASE SWITCHING AS A FUNCTION OF THE SOUND PRESSURE LEVEL AND TONE PULSES FREQUENCY

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Investigations were made of the discriminating ability of the ear during the switching on and off phases of the nonstationary tone pulses with a rectangular envelope curve. In the experiments there were determined the differential thresholds for the switching on and off phases of tone pulses with the frequency of 250 Hz and a time range of 8 ms—128 ms, 1000 Hz and 4000 Hz and a time range of 4 ms—128 ms, at 50, 65 and 80 dB levels of the sound pressure. The obtained results confirm that a change in the sound pressure level of the compared pulses of a selected duration and frequency does not significantly affect the discriminating ability of the ear with regard to the phase switching of the pulses.

О РАЗРЕШАЮЩЕЙ СПОСОБНОСТИ УХА ВО ВРЕМЯ ФАЗ ВКЛЮЧЕНИЯ И ВЫКЛЮЧЕНИЯ КАК ФУНКЦИИ УРОВНЯ ЗВУКОВОГО ДАВЛЕНИЯ И ЧАСТОТЫ ЗВУКОВЫХ ИМПУЛЬСОВ

В работе исследуется разрешающая способность уха во время фаз включения и выключения нестационарных звуковых импульсов с прямоугольной огибающей. В экспериментах определены дифференциальные пороги для фаз включения и выключения звуковых импульсов с частотой 250 гц и длительностью 8 до 128 мсек, 1000 гц и 4000 гц и длительностью 4—128 мсек, при уровне звукового давления 50, 65 и 80 дб. Полученные результаты подтверждают факт, что изменение уровня звукового давления сравниваемых импульсов выбранной длительности и частоты незначительно влияет на разрешающую способность уха с учётом фазы включения и выключения импульсов.

I. INTRODUCTION

A physical object carrying an information, i.e. an object able to establish at least a statistical link between the variables describing the physical situation of a certain object (the source of information) and the attached variables on the side of the receiver of the information, is called a signal. The signals as such can be characterized by the values of their physical parameters. A set of values of the

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physical parameters determines the signal accurately. In a similar way there is determined also a point in the n-dimensional space and consequently to each signal a point can also be assigned in a definite n-dimensional space. A set of these points then forms an n-dimensional continuity, namely the "signal space" [1]. The size of the coordinates in the signal space is determined by the values of the physical parameters of the corresponding signal.

In case of the sensorial organs being affected by external signals, a perception develops in the consciousness of the individual under certain conditions. This perception again can be characterized by a set of values of its sensory variables and consequently to each perception also a point can be attached in the "sensorial space".

The introduction of the terms "signal and sensorial space" is suitable as it allows to develop a simple formulation of problems occuring in the domain of the present sensory physics, in this case the sensory acoustics.

For example if we designate the distance between two signals S_1 and S_2 in the signal space dS, then the variable defined by the relation

$$A_S = \frac{1}{dS} \tag{1}$$

is called the signal afinity S_1 and S_2 [2]. The signal afinity of two signals is the measure of their discrimination.

If $A_S \rightarrow \infty$ the signals are identical and if $A_S = 0$ the signals have no affinity and consequently they can be clearly discriminated. Similarly also in the sensory space there can be introduced the variable

$$A_Z = 1/dZ \tag{2}$$

where dZ is the distance between two points (perceptions) in the sensorial space and which will be called the sensorial affinity of two perceptions. This variable again indicates the measure of discrimination of two perceptions; a person is able to discriminate two perceptions the better the lower the value of the affinity A_Z of the perceptions is [2].

Between the signal and sensorial variables there exist relations allowing the transformation of the signal variables to sensorial variables and conversely. The determination of these relations based on the sensory-physical experiments is the main task of the sensory physics nowadays. The solution of this key-problem is very exacting since unlike the scalar signal variables there exist two categories of the sensorial variables, namely the primary sensorial variables, which can be described by single-component quantities (for example the height), and the secondary variables described by the multicomponent quantities — vectors, tensors — in the sensorial space (e.g. colour of the signal). The determination of the relations between the points of the signal and sensorial space requires much experimental

work to be done also due to the fact that certain signal variables (e.g. the level of the sound pressure) affect various sensorial variables (e.g. the loudness, the height [3]). At present this problem is solved by investigating the effect of a certain physical parameter of the signal of combination with the other selected parameters and by using one of them as a variable within one experimental series; this of course requires to have at one's disposal a large set of experimental data.

As far as regards the informatory and theoretical aspect the threshold value of the discrimination of the signals is obviously of great importance, i.e. some critical value of the variable (2) at which the two signals become just discriminable (if taking as a basis the signals that cannot be discriminated). In general this critical value is defined as the minimal perceived difference of the physical parameter and is called the differential threshold (designated as DL) for this parameter [4].

The first experimental studies on the discriminating ability of the ear were devoted to the measurement of the DL-value of the frequencies, the intensity and the duration of the acoustic signals. Later it was found to be of interest to measure the DL-value also for other parameters, e.g. the envelope curve [5] or the switching phases of short sinusoidal tone pulses with a rectangular envelope curve both with a whole number [6] or a divided number [7] of cycles. In the experimental work [7] there was measured the differential threshold for the switching on phase — the initial phase (DL_φ) and the switching off phase — the final phase (DL_ψ) as a function of the frequency and duration of the pulses. In this connection the question to what extent the DL_φ and DL_ψ are dependent on the sound pressure level of the signals seems to be of interest.

In this submitted experimental study the results obtained in connection with the DL_φ and DL_ψ dependence on the level of the sound pressure and the frequency of the tone pulses (at selected values of duration) are presented.

II. EXPERIMENTS

The discriminating ability of the ear with regard to the parameters of the switching on and switching off phases as a function of the sound pressure level and of the frequency of pulses was measured at durations of the pulses corresponding to their threshold height, the tone — pitch duration threshold (as defined by Doughty and Garner [8]), and at the duration of 128 ms. The frequencies of pulses were 250, 1000 and 4000 Hz. The sound pressure levels were 50, 65 and 80 dB (measured as the levels of stationary signals from which the given pulses were cut out); these levels cover the range of most real acoustic signals.

II. 1. Method and procedure

The subject situated in an anechoic chamber, received a pair of tone pulses. The response from her followed immediately. The parameters od the first applied couple of pulses (standard) during one pulse train remained unchanged and its phases of switching were always 0°. The parameters of the second (comparative) pulse were, except for the switching phase, identical with those of the first one. The interval between the couples of pulses (also defined as the interval between the particular experiments within one pulse train) was long enough in order to give the tested person the chance to relax and to register the responses. The switching phases of the comparative pulse had in the interval of 0°—35° values corresponding gradually to the round multiples of 5°, the next value was 45° and then up to the value of 90° the phases increased by 15°. With such a choice of the phase switching changes the entire range of responses from 100 % "equal" up to 100 % "unequal" was distributed along 6—9 measured values or points, respectively. This number of points is considered to be optimal (e.g. according to Ref. [9]).

Thus the set of parameters of the applied pulses was a finite one; the comparative pulse was marked in the signal space by a set of preselected values of the physical parameters and for this reason the experimental method of the constant stimuli was applied.

The task of the tested person was to estimate as to whether the applied couple of pulses is equal (positive responses) or unequal (negative response). In the case of

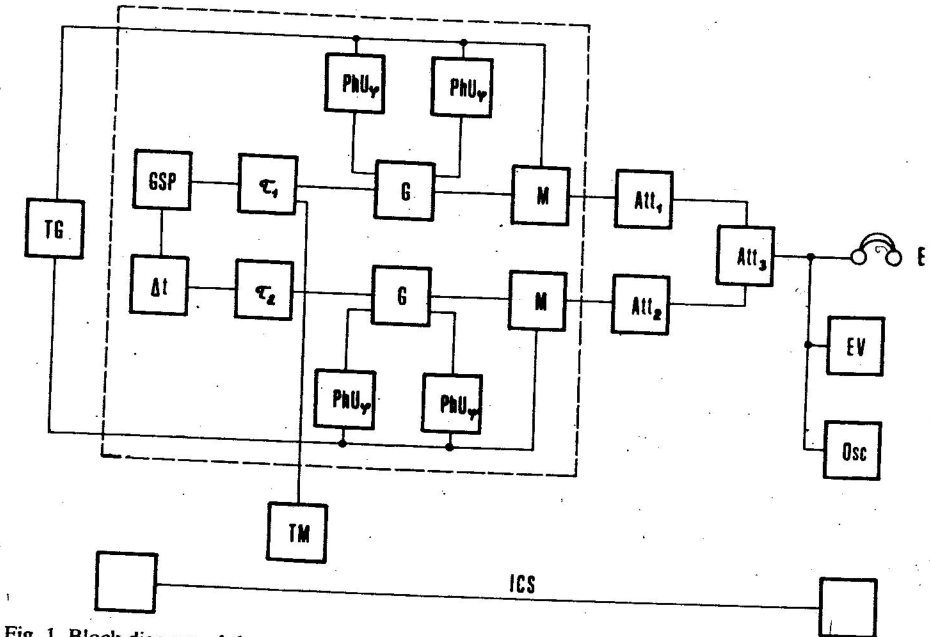


Fig. 1. Block diagram of the apparatus. TG — tone generator B & K 1024; ES-2 — electronic switch; TM — chronometer Radiometer MSM 1a; Att_{1-3} — attenuator RFT X_0 716; Osc — oscilloscope TESLA BM 462; EV — electronic voltmeter B & K 2409.

unequal signals (height, colour, etc.) the tested person was not obliged to discriminate the signals except if voluntarily giving information on such questions after several pulse trains.

The measuring procedure was as follows: The experimentator selected the switching phases of the comparative pulse of 0° and informed the tested person by means of an optical signal that a couple of acoustic signals would follow after an interval of about 0.5—1 sec.; the acoustic signals were given by means of a manual starter. After a positive response of the subject the experimentator increased the registered switching phase of the comparative pulse up to a value at which the responses of the tested person were definitely negative. After the increasing series — as far as regards the switching phases of the comparative pulse — there followed a decreasing series, which began with the "unequal pulses". During the intervals between the couples of pulses the experimentator decreased the switching phase of the comparative pulse.

One series of the measurements had four increasing and four decreasing series and lasted about 20—30 min.

Prior to each measurement the tested person had enough time for training owing to the fact that her responses given during the introductory period of the test were not registered; the subject of course had not been informed of this fact.

II. 2. Apparatus

The block diagram of the apparatus is shown in Fig. 1. The basic part of the equipment is an electronic switch ES-2 of laboratory provenience able to generate pulses with a rectangular envelope curve with an eligible initial and final phase of the carrier signal which can be independently adjusted within the preselected interval. Owing to the fact that the measuring method required the application of a couple of pulses in the course of a definite time sequence, it was necessary to use a two-channel electronic switch. In the first channel the so-called standard pulse was generated and in the second channel a pulse was generated with an initial and final phase varying within a preselected time interval.

Both channels are controlled by a generator of starting pulses GSP which controlled the linkage units, i.e. the so-called timing unit τ_1 of the first channel and the lagging unit Δt of the second channel. The lagging was adjustable within the range of 1 ms — 3 s. The timing unit of both channels τ_1 and τ_2 were identical and generated rectangular pulses 1 ms — 3 s long that were fed into the electronic gates G, where the modulating signal was generated in dependence on the control pulses generated in the phasing units PhU_φ (initial phase) and PhU_ψ (final phase) — [10]. The jump-by-jump selection of the initial and final phase was possible in the range from 0° up to 180°.

The obtained modulating signal as well as the signal from the tone generator TG were supplied to the amplitude modulators M, where the required signal was generated. The obtained pulses with a rectangular envelope curve were brought to the attenuators Att_1 and Att_2 allowing the adjustment of the levels of the particular pulses. In the next part of the equipment both channels were connected. The whole level of both pulses was adjustable by means of the attenuators Att_3 from where the signal was brought to the earphones E, the entry of which was permanently connected with an electronic voltmeter EV and an oscilloscope Osc.

The duration of the pulses was controlled by a time measuring device TM. The equipment, except the earphones, was installed in an operation room in front of the anechoic chamber, in which the subject, isolated from the environment (−50 dB), was tested.

Between the tested person and the experimentator there was installed a multiple communication system ICS composed of two parts, namely the acoustic intercommunicating system allowing in case of need an intercommunication with the subject, as well as a permanent control of his health state during the experiments (whether quiet, coughing, etc.) and the optical intercommunicating system of signal lamps enabling the tested person to signalize the values of the applied signals.

The equipment was carefully calibrated (duration and level of the pulses). The correct adjustment of the level and duration of the pulses was controlled after ending each series of measurements. The stability of the adjustment of the initial and the final phase of the pulses was very good; this parameter played an important role in the construction of the electronic switch (selection of a convenient switching of the phase units, jumping change of the phase, etc.). The whole equipment was supplied from a stabilized network.

II. 3. Results

With regard to the applied experimental method of the constant stimuli and in agreement with the general definition of the differential threshold, DL, for a concrete phase of switching is defined as the value of such a phase (in degrees) to which there corresponds a 50 % probability indicating that two tone pulses differring by this phase of switching can be discriminated; thus it can be assumed that this is a variable of a statistical character (all relations in the domain of sensorial physics have such a character). The experimental points (negative responses) obtained from the tested person during the particular series of measurements represent the empiric probability, namely that a concrete comparative pulse coupled with a given standard pulse, is perceived as an "unequal" pulse; their distribution is an approximation of the integral curve of the normal distribution. There points were approximated by a straight line [11] by using the least square method. The point in which the obtained straight line intersects the probability level 0.5 is identical with the point in which this level would be intersected by the

Table 1

Differential threshold for the switching on phase and switching off phase of the tone pulses as a function of the sound pressure level.

f[Hz]	duration [ms]	L[dB]	50		65		80	
f[Hz]			DL[°]	SO[°]	DL[°]	SO[°]	DL[°]	SO[°]
250	8	φ	17.42	3.61	16.96	1.35	17.25	2.36
		ψ	16.09	2.18	15.12	0.59	15.75	1.14
	16	φ	23.22	9.77	18.6	1.58	17.16	0.92
		ψ	16.05	2.38	15.36	1.18	14.51	1.18
	128	φ	27.47	4.35	27.87	6.62	26.36	7.76
		ψ	26.72	7.68	26.55	5.5	26.64	8.51
1000	4	φ	17.51	5.05	16.68	3.58	17.35	1.39
		ψ	16.73	4.16	17.45	0.7	18.3	1.87
	8	φ	18.03	2.47	16.91	1.59	18.95	0.89
		ψ	19.5	2.19	18.01	1.67	19.8	3.4
	128	φ	77.47	33	44.66	3.31	57.71	6.06
		ψ	59.6	15.42	46.56	2.76	54.67	3.04
4000	4	φ	18.43	3.1	20.64	5.28	21.01	3.98
		ψ	17.53	2.4	19.64	7.52	21.29	3.6
	8	φ	16.86	2.32	16.46	3.29	20.54	4.41
		ψ	18.15	2.81	15.52	3.27	19.02	5.79
	128	φ	47.67	2.54	48.77	4.79	48.54	6.91
		ψ	45.81	2.69	47.9	7.42	49.47	5.24

integral curve of the normal distribution [12]. This factor has been used in the statistical evaluation of the obtained results in which except DL — as the average value obtained from four tested persons — the corresponding deviation was also computed.

The functional dependence of DL_φ and DL_ψ on the level of the sound pressure of the pulses was investigated by using combinations with their other physical parameters that can be expected by the following functional relations:

$$DL_\varphi = F_1(f, L, \tau); \quad DL_\psi = F_2(f, L, \tau); \quad \Phi_0 = \Psi_0 = \text{const.} = 0° \qquad (3)$$

a) $f = 250$ Hz, $L = 50$ dB, 65 dB, 80 dB, $\tau = 8$ ms, 16 ms, 128 ms

b) $f = 1000$ Hz, $L = 50$ dB, 65 dB, 80 dB, $\tau = 4$ ms, 8 ms, 128 ms

c) $f = 4000$ Hz, $L = 50$ dB, 65 dB, 80 dB, $\tau = 4$ ms, 8 ms, 128 ms.

The minimum duration of the pulses corresponded to the height limit for the corresponding frequency, maximum of 128 ms. In addition the observed depend-

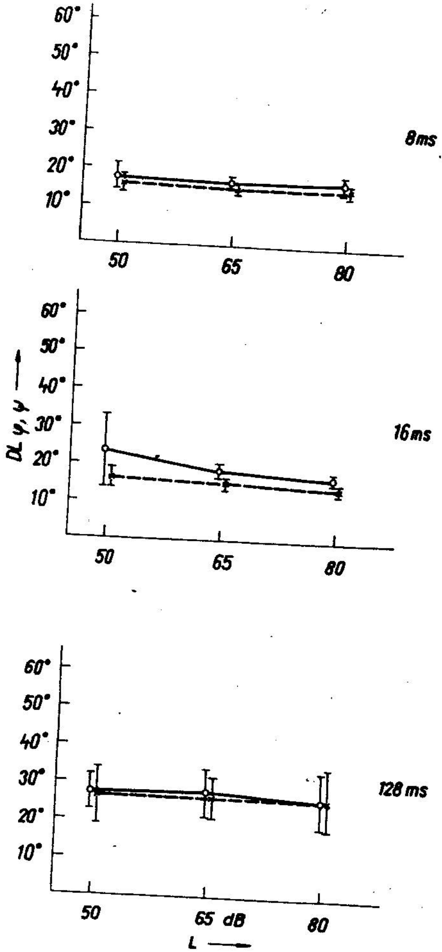


Fig. 2a Differential threshold for the switching-on phase (solid curve) and the switching-off phase (dashed curve) of the tone pulses 250 Hz as a function of the sound pressure level.

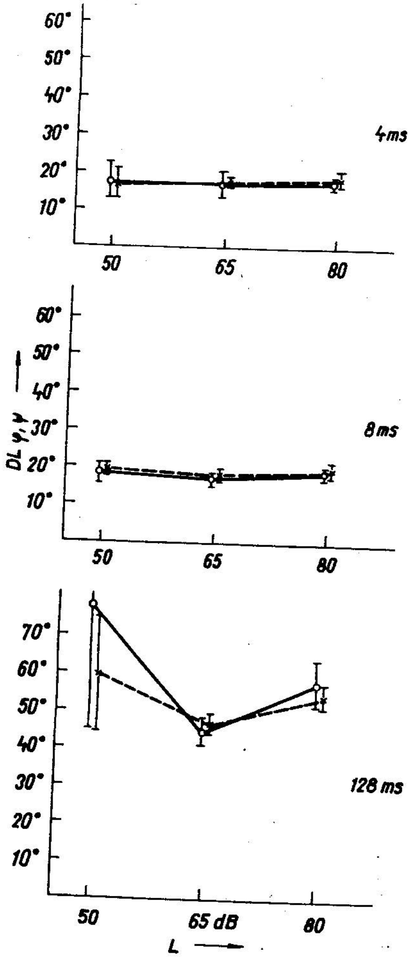
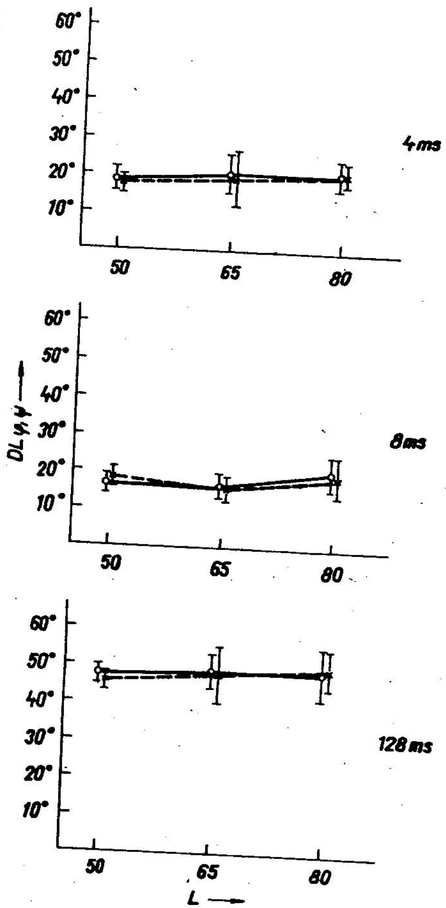


Fig. 2b Differential threshold for the switching-on phase (solid curve) and the switching-off phase (dashed curve) of the tone pulses 1000 Hz as a function of the sound pressure level.

ence was also investigated at the duration which was near the tone-pitch duration threshold, which is similarly as the limit height — dependent on the pulse frequency [8].

The results obtained in the experiments are described in Table 1 and in Figs. 2a, b, c, which prove that the change of the sound pressure level — if keeping the other parameters of pulses unchanged — does not affect significantly the discriminating ability of the ear with regard to the parameter of the switching phase. Like in work

Fig. 2c Differential threshold for the switching-on phase (solid curve) and the switching-off phase (dashed curve) of the tone pulses 4000 Hz as a function of the sound pressure level.



[7] the results of our measurements also confirm that no significant differences exist between DL_φ and DL_ψ in a concrete combination of the physical parameters of the pulses. From the obtained results also the conclusion can be drawn that a prolonged duration (and at the frequency of 1000 Hz also the lowering of the sound pressure level) significantly contributes to the enlargement of the dispersion of the responses obtained from the tested persons.

III. DISCUSSION

The fact that the sound pressure level does not affect to a large extent the DL_φ and DL_ψ values is from the experimental-technical point of view to some extent rather surprising, since there is reason to assume that by increasing the sound pressure level and by taking into consideration the significance of the click at the end and, respectively, the start of the pulse, the colour of the comparative pulse — at a given change in the phase switching — will be better discriminable. Taking as a basis this assumption it can be concluded that the values of DL_{φ}, and DL_{ψ} should be lower when the level of the sound pressure rises; this, however, was not proved by the experimental results.

On the other hand, however, the obtained results seem to satisfy the physical and mathematical part of the problem as it is true that a change of the level of the pulses does neither change the relative spectral density of their amplitudes nor their time behaviour. The key experience made in this experiment and leading to the conclusion that the differential thresholds with regard to the switching phases of the tone pulses in a given combination with their other physical parameters show no significant functional dependence on the level of their sound pressure, is in conformity with the results obtained in measurements of the given dependence for the case of pulses with an undivided number of cycles [13]. Based on the obtained results we conclude that in the following experiments on the discriminating ability of the ear with regard to the phase switching it will be sufficient to carry out series of measurements only in the range of the sound pressure mean levels and thus to obtain a picture of the differential thresholds for a relatively wide range of sound pressure levels of the signals; this certainly will spare time and lower the costs of the experimental work planned for the future.

IV. CONCLUSIONS

The results obtained in our experiments allow to draw the following conclusions:

1. Within the range of the sound pressure levels of the sinusoidal pulses with a rectangular envelope curve 50—80 dB and a duration of 4—128 ms there exists a non-zero set of acoustical signals which can be discrimined on the basis of differences occuring during the switching of the phases.

2. The change of the sound pressure level of the compared pulses at a selected duration and frequency has no significant effect on the discriminating ability of the ear with regard to the phases of switching the pulses.

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