acta phys. slov. 27. (1977), No. 2

THEORETICAL ASPECTS OF SOME SENSORY-ACOUSTICAL AND BIO-ACOUSTICAL EXPERIMENTS

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The problems of the theoretical interpretation of the experimental results from the point of view of the place principle and the time course principle of the theory of hearing are shown. The corrective conception of the theory of hearing is formulated. This conception enables the simple interpretation of the known experimental results.

ТЕОРЕТИЧЕСКИЕ АСПЕКТЫ НЕКОТОРЫХ СЕНСОРНО-АКУСТИЧЕСКИХ И БИО-АКУСТИЧЕСКИХ ЭКСПЕРИМЕНТОВ

В работе рассматриваются проблемы теоретической интерпретации экспериментальных результатов с точки зрения принципа места а принципа течения времени теории слуха. Формулируется поправочная концепция теории слуха. Эта концепция позволяет простым образом интерпретировать известные экспериментальные данные.

I. INTRODUCTION

To follow the transformation of the physically defined auditory signal up to the final sensory phenomenon is for the present impossible. It is therefore useful to concentrate the effort first of all upon the sensory-acoustical experiments, which enable to solve the questions fitting into a broader theoretical framework. Although the discussion arising from the results of the mentioned experiments cannot ignore ideas of a more or less hypothetical character, it has nevertheless at least a positive significance in that it stimulates serious scientifically grounded research of the theoretical and experimental physicists, physiologists and biochemists working in this field.

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II. SUMMARY OF THE MOST IMPORTANT FACTS AND THEIR STANDARD THEORETICAL INTERPRETATION

II.1. Summary of the most important facts

II.1.1. The pitch of the sinusoidal sound waves (tone) affecting the human ear is proportional to the frequency of the waves. The response of the inner ear to the falling sinusoidal waves is localised [1].

II.1.2. In the case of the auditory signal being composed of several components which are sufficiently separated from each other in frequency — more then by the widths of the particular critical band [2] — every component is separately perceived [3], [4].

II.1.3. The activity of the inner ear as the response to the effect of the external (also stationary) sinusoidal signal is characterized by a non-sharp maximum [5].

II.1.4. The perception of an acoustical signal consist of two or more sinusoidal components is marked at higher sound pressure levels by the fact that besides the "primary tones" there seem to appear also combination tones [6].

II.1.5. a) When a signal consists of several harmonically related components, it is usually perceived as a tone with the pitch corresponding to the basic harmonic one, even when its amplitude is zero [7—10]. b) However, the lower harmonic components are sometimes perceived individually.

II.1.6. The nervous system is capable to produce synchronic impulses [11]. The upper limit of the synchronism lies in the range of frequency of about 4000 Hz.

The most important facts summarized above were not arranged chronologically with respect to their discoveries but more according to the degree of their correspondence with the basic principles of the theory of hearing.

II.2. Interpretation of experimental results on the basis of the place principle of the theory of hearing

The main ideas of the theoretical principle, nowadays called the place principle, were introduced by Helmholtz, who is generally considered to be the founder of the modern theory of hearing. Helmholtz [13] built up the theory of hearing on the ground of three hypotheses:

1. The analysis of sound is carried out in the inner ear by the mediation of great number of resonators which are tuned to the various frequencies — from the low up to the high ones.

2. The pitches of the individual tones correspond to the particular activated fibres in such a way that the tone pitch decreases gradually from the basal to the apical end of the Corti organ.

3. The transmission of sound by the auditory apparatus is characterized by nonlinear distortion.

It is impossible to admit — on the ground of contemporary physical and physiological facts — the application of resonance in the response of the inner ear. However, direct experimental results (mainly those of Békésy [5]) and the mathematical treatises on the dynamics of the cochlea (Zwislocky [14]) seem to give a high degree of plausibility to the assumption of the correspondence of the place of the inner ear activity and the pitch of the perceived tone (which, nowadays, is the essential point of the place principle of the theory of hearing).

On the basis of the place principle it is possible to explain the facts of the above summary as follows:

II.2.1. (The relation place pitch). The harmonic waves call forth according to their frequencies maxima of the inner ear activity. The particular nervous fibres mediate information about the tone pitch.

II.2.2. (The perceptibility of the composed sound components.) The several-component signal is perceived by the same mechanism as that being composed of various pitches.

II.2.3. (The non sharp maxima of the inner ear activity). A relatively high frequency-analysing power of the auditory apparatus may be explained by supposing that the nervous system transmits the activity from a relatively narrow range of the Corti organ only (a further narrowness might take place during a neural way, within a synapsis, etc.).

II.2.4. The combination tones are a logical consequence of a nonlinear distortion in the auditory apparatus.

II.2.5. The problem under II.1.5.a (perception of the harmonic sound as one tone) can be explained only with difficulty by the place principle without introducing other assumptions (e.g. the creation of connections between the ranges of the Corti organ responding to harmonically related tones). The fact of II.1.5.b (perceptibility of the lower components of the harmonic sound) can on the other hand be explained simply.

II.2.6. The synchronization of nervous excitations by an external signal is not in contradiction with the place principle (there is little probability that the information on the tone pitches with a frequency of more than 5000 Hz would be mediated by the mechanism of synchronization). It may be admitted that the higher the intensity of the signal, the higher is the number of nervous excitations created in the apparatus of hearing.

II.3. Interpretation of experimental results on the basis of the time-course principle of the theory of hearing

The individual above mentioned facts can be explained on the basis of the time-course principles as follows:

II.3.1. The pitch of an auditory signal is derived from its time-course by the mechanism of synchronization of the neuron extitations with maxima in the signal time-course. The shorter the signal period is, the higher seems the signal without regard to the (harmonic or only periodic) character of the signal (periodicity pitch).

The fact that the harmonious signal activates various parts of the basilar membrane is not important for the pitch perceptions. The place of the basilar membrane activity may be important for the determination of the timbre of the perceived signal.

II.3.2. The perceptibility of the composed sound components on the basis of the time-course principle is explained with difficulty.

II.3.3. The fact that the maxima of the inner ear activity are not so sharp introduces complications for the place principle (in its contemporary form), especially with regard to the considerable frequency-analyzing power of the ear. On the other hand, the theory based on the time-course principle has no problems explaining this fact because the activated part of the basilar membrane is not correlated with the pitch of the signal.

II.3.4. The explanation of the combination tones without the assumption of the nonlinear distortion, as described by Helmholtz, is not known.

II.3.5. The first part of phenomenon II.1.5.a (perception of the harmonic sound as one tone) is in agreement with the basic assumption of the time-course principle; phenomenon II.1.5.b (the perceptibility of the lower components of the harmonic sound) — similarly as that in point II.3.2, is difficult to explain in this way.

II.3.6. The fact that one neuron can react up to 50 times in a second created at first serious objections to the assumption that the pitch of the signal is derived from its periodicity by the mechanism of the synchronization of neurons. Provided that the group of neurons realize the transmission of excitations, e.g. a neuron "n" reacts on the "n-th" cycle (the volley principle), this problem loses its topicality from the point of view of the time course principle.

III. SOME MORE RECENT EXPERIMENTAL RESULTS, AN OUTLINE OF THE PROBLEMS OF THEIR THEORETICAL INTERPRETATION

Research into the influence of the switching phases of short tone pulses (i.e. the hase angles of the short sinusoidal pulses in their switch-on, resp. switch-off, oment) with a rectangular envelope resulted in conclusions, which in consequ- ce on the facts of Sect. II.1. can be summarized in the following points:

III.1. The pitch of the tone pulses (mainly those with a duration near to the ration threshold of the tone-pitch) grows monotonously with the increase of both the switch-on and the switch-off phase angles [15], [16]. (Relation switching ase — pitch of short tone pulses).

.2. Two tone pulses are sensorily distinguishable when the difference between switching phases is sufficiently great. The difference in their timbre helps to distinguish these pulses [17—19]. (Sensory distinguishability of the tone pulses as regards the differences in the switching phases.)

There are some problems with the theoretical interpretation of these results from the point of view of the place principle in its contemporary form similarly as with the explication of fact II.1.3. (the non sharp maxima of the inner ear activity). It concerns namely the confrontation between little sharpness of the maxima of the Corti organ activity and the high sensitivity of the ear to the differences in the signal frequencies. Furthermore, another problem arises — it is impossible to find a simple correspondence between the maxima of the amplitude spectral densities and the points of the subjective equality for frequency [15].

The explanation of fact III.1. (relation switching phase — pitch of short tone pulses) is impossible on the basis of the time-course principle. The duration of the tone pulse period is equal at every value of the switching phase. Therefore it is difficult to find a satisfactory interpretation of the experimental result III.1. on the basis of the periodicity pitch.

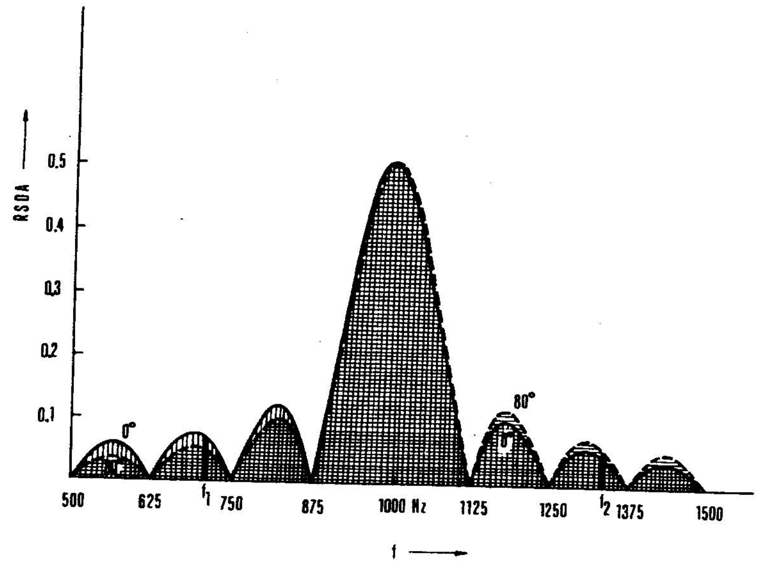

Fig. 1. The relative spectral density of amplitudes (RSDA) of the tone pulse of the frequency of 1000 Hz, duration 8 ms, for the initial phase 0° (the vertically hatched area under the full line cover curve) and 80° (the horizontally hatched area under the dashed cover curve). The figure illustrates the spectrum of the first and the last line of the Table 1. The frequency interval is marked by thick lines for which the point of balance according to (6) is in good agreement with the experimental results on pitch perception. The signal timbre is connected with the distribution of its energy, the pitch with the position of the point of balance of the amplitude spectral density, according to the conception formulated in Sect. IV.2.

IV. DISCUSSION

From the above mentioned survey it follows that the explanation of facts II.1.2 (perceptibility of composed sound components), II.1.4 (combination tones), II.1.5.b (perceptibility of the lower components of the harmonic sound), III.1. (relation switching phase — pitch of short tone pulses) is problematic on the basis of the time-course principle conception, the explanation of facts II.1.3 (non-sharp maxima of the inner ear activity), II.1.5a (perception of the harmonic sound as one tone), III.2. (sensory distinguishability of tone pulses with respect to differences in the switching phases) on the basis of the place principle conception.

To formulate more acceptable explanations of the experimental results we shall start from the physical-mathematical aspect of recent experimental results.

IV.1. The physical-mathematical aspect of recent experimental results

When discussing the differences of the sinusoidal tone pulses differing from each other only by the switching phase parameters it is convenient to consider short pulses, or, to be more exact, non-stationary ones (e.g. to 125 ms [20]). Therefore, in the following we shall take into consideration the type of signals with a rectangular envelope.

A sinusoidal tone pulse with n periods (n is a rational number), with the duration of one period $1/f_0$ (f_0 means the frequency of the pulse), with the amplitude of acoustic pressure p_0, with a rectangular envelope and a switching-on phase φ, can be expressed by the equation:

$$p(t)=\begin{cases}0 & \text{for } -\infty<t<0\\ p_0\sin(2\pi f_0 t+\varphi) & \text{for } 0\leq t\leq n/f_0\\ 0 & \text{for } n/f_0<t<+\infty,\end{cases} \qquad (1)$$

where $p(t)$ means the instantaneous acoustic pressure. This pulse fulfils the Dirichlet conditions and can therefore be expressed by the Fourier integral [21]

$$p(t)=k\int_0^{\infty}[a(f)\cos 2\pi ft+b(f)\sin 2\pi ft]\,df, \qquad (2)$$

where

$$a(f)=k\int_{-\infty}^{\infty}p(t)\cos 2\pi ft\,.\,dt$$
$$b(f)=k\int_{-\infty}^{\infty}p(t)\sin 2\pi ft\,.\,dt\,. \qquad (3)$$

The Rel. (2) can be rearrangered in the form $p(t)=k\int_0^{\infty}r(f)\cos[2\pi ft-\vartheta(f)]\,df$, where

$$r(f)=\sqrt{a^2(f)+b^2(f)} \quad \text{and} \quad \vartheta(f)=\operatorname{arctg} b(f)/a(f)\,. \qquad (4)$$

By applying integrals (3) to pulse (1) we obtain for the components of the relative spectral density of amplitudes

$$a(f,n,\varphi)=\frac{p_0}{4\pi^2}\left\{\sin\varphi\left[\frac{\sin\frac{2\pi n}{f_0}(f_0-f)}{f_0-f}+\frac{\sin\frac{2\pi n}{f_0}(f_0+f)}{f_0+f}\right]+\right.$$
$$\left.+\cos\varphi\left[\frac{2f_0}{f_0^2-f^2}-\frac{\cos\frac{2\pi n}{f_0}(f_0-f)}{f_0-f}-\frac{\cos\frac{2\pi n}{f_0}(f_0+f)}{f_0+f}\right]\right\}$$
$$b(f,n,\varphi)=\frac{p_0}{4\pi^2}\left\{\cos\varphi\left[\frac{\sin\frac{2\pi n}{f_0}(f_0-f)}{f_0-f}-\frac{\sin\frac{2\pi n}{f_0}(f_0+f)}{f_0+f}\right]+\right.$$
$$\left.+\sin\varphi\left[\frac{2f}{f^2-f_0^2}-\frac{\cos\frac{2\pi n}{f_0}(f-f_0)}{f-f_0}-\frac{\cos\frac{2\pi n}{f_0}(f+f_0)}{f+f_0}\right]\right\}. \qquad (5)$$

The spectral density of amplitudes (5) depends therefore on the frequency, the duration and the switching phases of the particular pulse.

The calculations of the spectral density of amplitudes show [15] that the pulse whose switching phases are non-zero, has the main maximum shifted a little in the direction of the higher frequencies compared with the pulse with the zero switching phases. Furthermore its spectral density of amplitudes at lower frequencies (than the frequency of the main maximum) is lower and at higher frequencies higher than at the zero phase switching pulse. The described tendency is evident from Fig. 1.

The influence of the change of the switching phase on the pulse spectrum may be characterized also in such a way that its increase results in a shift of the point of balance of the spectral density of amplitudes which is given by the relation

$$f_{PB}=\int_{f_1}^{f_2}r(f)\,f\,df\Big/\int_{f_1}^{f_2}r(f)\,df \qquad (6)$$

in the direction of the higher frequencies.

To judge the influence of the individual switching phases we have calculated the spectral density of amplitudes of the non-stationary tone pulses with an integral and non-integral number of periods. It was found that the shift of the point of balance of the amplitude spectral density in the direction of higher frequencies

Table 1

The influence of the switching phase on the localization of the amplitude spectral density with regard to the frequency axis. The integration limits: 700—1335 Hz.

	Frequency of pulse [Hz]	Switching-on phase φ	Switching-off phase ψ	Duration of pulse [ms]	Frequency of point of balance of SDA
1	1000	0°	0°	8	1000.2
2	1000	40°	0°	7.75	1002.98
3	1000	0°	40°	8.25	1002.97
4	1000	40°	40°	8	1004.4
5	1000	80°	0°	7.50	1006.6
6	1000	0°	80°	8.50	1006.2
7	1000	80°	80°	8	1013.0

created by the switching-on phase increase for a certain angle (leaving the zero phase of the switching-off unchanged), was less than the shift caused by the simultaneous increase of the switching-on and the switching-off phases for the same angle. A similar effect was found upon the increase of the switching-off phase (see Table 1).

Further, calculations show that the shift of the point of balance of the spectral density of amplitudes caused by a given switching phase change monotonously increases with a shortening of the pulse. The importance of the switching phase decreases with the pulse prolongation from the spectral point of view. The restriction of the study to non-stationary pulses (mentioned at the beginning of the paragraph) is therefore easily comprehensible.

IV.2. Formulation of the corrective theoretical conception with regard to recent experimental results

The following conception enables a more acceptable explanation not only of facts III.1. (relation switching phase — pitch of short tone pulses) and III.2. (sensory distinguishability of tone pulses with respect to differences in the switching phases) but also of the previous ones. When dealing with an auditory information, the system starts with the dispersion of the signal energy. The signal energy is equilibrated by the auditory system, the localisation of its point of balance given by expression (6) on the frequency scale being decisive for the pitch appreciation, and the total distribution of the signal energy determines the timbre. The number of nervous excitations caused by the signal for a time unit remains as the sensory-physical parameter for the appreciation of the signal loudness.

The advantage of this conception is based first of all on the fact that it explains the perception of stationary and non-stationary signals on the same principle. It is

namely evident that the (energetic) point of balance (with regard to the frequency axis) of the stationary signal will be identical with its carrier frequency, and moreover, the problem of the high frequency discrimination power and not very sharp maxima of the basilar membrane activity can be dismissed.

The explanation of fact II.1.5a (perception of the harmonic sound as one tone) remains for the moment to a certain degree problematic. If we admitted that the auditory system appreciating the signal which bears an expressive information in the time region (the signals used in experiments [7—10] are characterized by expressive, periodically repeated maxima) might utilize it in certain limiting suppositions (e.g. with regard to the upper frequency limit) for the appreciation of pitch, the explanation of fact II.1.5a would become much simpler. To accept it would mean to approach some place — time conception of the theory of hearing. The tendency to relate these principles, is not new. It may be already seen in the work of, e.g. Wever [22] but also in the works of contemporary authors, e.g. Zwicker [2].

V. THE INFORMATION-THEORETICAL ASPECT OF RECENT EXPERIMENTAL RESULTS

Experimental results III.1. (relation switching phase — pitch of short tone pulses) and III.2. (sensory distinguishability of tone pulses on differences in the switching phases) show that there exists a non-zero set of auditory signals for which the switching phase parameter is the carrier of information. The distinguishability of signals — sinusoidal tone pulses with a rectangular envelope — with a given switching phase difference (with the other parameters preserved identical) decreases with an increase of the signal duration. The signal parameter of the switching phase obviously corresponds with the sensory parameters of the pitch and the timbre.

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Received July 1st, 1975