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PSYCHOACOUSTICAL EQUIVALENTS OF TUNING CURVES AS DETERMINED BY THE POST-STIMULATORY MASKING TECHNIQUE

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The method and results of measurements of psychoacoustical tuning curves covering about 6500 individual judgements are described. Three experienced music students served as subjects in the experiment. The slopes of tuning curves obtained reach 1040 to 2200 dB/oct at the characteristic frequency 1 kHz. With reference to KIANG'S [7], TONNDORF'S [16] and MØLLER'S [10] data the importance of functions of the cochlear nucleus or the higher neurons in the perception of pitch is discussed.

1. Introduction

Since KIANG'S [7] investigation of the 8th nerve bioelectrical activity which resulted in the so-called «tuning curves» determining the frequency resolving power of an ear, much effort has been spent on attempts to find their hydromechanical or psychoacoustical equivalents.

These attempts have been largely induced by a significant disproportion between the well accepted and widely published data pertaining to the excitation patterns of the basilar membrane, obtained from the direct visual examination [1, 2] or inferred from the direct masking patterns [20], and the results of investigation of bioelectrical activity or of the difference limen for frequency [11, 12].

The slopes of the basilar membrane excitation patterns, obtained by BÉKÉSY from direct observation, were small: about 20 dB/oct above the frequency of excitation and about 6 dB/oct below this frequency.

To achieve vibration amplitudes of the basilar membrane sufficiently large for direct observation with the use of an optical microscope, the sound pressure levels of about 140 dB were used in this experiment. Such pressure levels could have resulted in substantial nonlinearities.

RHODE [14] using the Mössbauer technique obtained, at 7 kHz, slopes of about 100 dB/oct and 24 dB/oct, respectively, above and below the point of maximum excitation. RHODE used Squirrel Monkeys in his experiment.

KOHLLÖFFEL'S [8] investigation using laser light on Guinea Pig post-mortem samples, at the same frequency of excitation, gave slopes of about

56 dB/oct and 10 dB/oct respectively. In living animals, at 28 kHz and at a sound pressure level of about 100 dB, he was able to find slopes of 100 to 130 dB/oct above and 7 to 9 dB/oct below the point of maximum excitation.

The slopes of *tuning curves* [1]) determined by KIANG as calculated by WILSON [19] for the region above *CF* reach 200 dB/oct. WILSON also cited EVANS [3] unpublished data which show slopes reaching 200 to 500 dB/oct.

Psychoacoustical equivalents of tuning curves as determined by HOUTGAST [4] using the pulsation-threshold method, do not show the slopes to be substantially higher than 200 dB/oct above the *CF*. The slopes of psychoacoustical tuning curves determined by ZWICKER [21] using the direct masking-method and threshold tracking with Békésy's automatic audiometer, reach about 150 to 200 dB/oct for $CF = 2$ kHz. ZWICKER's data are thus comparable with those of HOUTGAST [4]. Significantly higher slopes, up to about 950 dB/oct in the range above *CF* 2 kHz and 560 dB/oct above *CF* 1 kHz have been found by VOGTEN [18] who used the poststimulatory masking method of measurement.

In the present report the results of a psychoacoustical investigation of tuning curves are presented. The experiments were run using the poststimulatory masking technique similar to that used by VOGTEN [18], but with a slightly different construction of the time paradigms of signals used. This research has been induced by the promising data, obtained in the earlier experiments pertaining to pitch shifts in the poststimulatory masking [5, 13], which indicated the existence of quite substantial values for the slopes of psycho-acoustical tuning curves at $CF = 1$ kHz, even greater than those determined by VOGTEN [18] for $CF = 2$ kHz.

2. Procedure

The attempt of this experiment was to determine the poststimulatory masking curves for short (50 ms) 1 kHz tone pulses at a 15 dB sensation level L_m masked by comparatively long tone pulses at sensation levels $L_M + L_m$ and frequencies in the vicinity of the maskee frequency. A two-alternative-forced-choice procedure was used. The stimuli were presented to the listeners according to the time paradigm given in Fig. 1. The maskee was present in the paradigm only in 50 % of successive presentations and was switched in and out noiselessly in a semi-random manner.

After each presentation a listener signalled with a push-button whether he had detected the maskee in the presented paradigm, or not.

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[1]) The term *tuning curves* refers to the dependence of the intensity of exciting tone pulses on the tone frequency, with the assumption that the nerve fibre which is in contact with the microelectrode reacts to each of the pulses with the same number of spikes. The frequency at which maximum sensitivity is observed has been called the *characteristic frequency* or *CF*.

All listeners in all sessions passed a routine 5 min. screening test before they were allowed to the experimental runs which consisted of 18 successive series lasting 2 min. each with 5 min. intervals every 6 series.

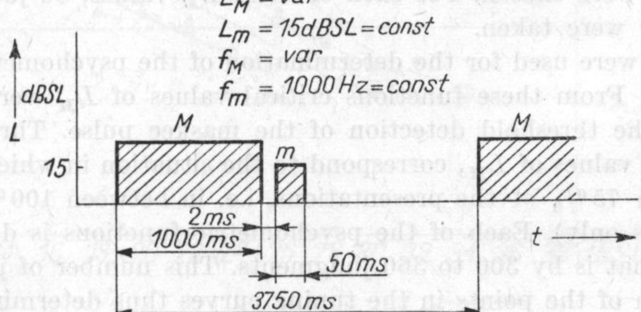

Fig. 1. Time paradigm of the stimuli used in the determination of psycho-acoustical tuning curves

The research was carried out using a three-channel analogue modulator controlled by a programmable time counter [6]. Sine signals stable to 10^{-4} per day were fed to the inputs of the modulator. The frequencies of these signals were measured with an electronic counter with an accuracy of 10^{-4}.

These sequences of stimuli, defined in the time domain to an accuracy of $\pm$ 1 ms, were presented in an anechoic chamber using a QUAD electrostatic loudspeaker and power amplifier.

In a pilot study a modification of procedure in this experiment was introduced, namely two function modules were added to the analogue modulator, to shape the initial and final transients of tone pulses. These were a linear slope function module for the masker and a Gaussian function module for the maskee. The slopes of the psycho-acoustical tuning curves obtained in these pilot measurements were comparable to those reported by Vogten [18].

In the final version of the experimental set-up both function modules were eliminated (switched out). To reduce to some extent the spectrum width of the signals processed, *LP* filters with cut-off frequencies of 1.25 kHz and slopes of about 300 dB/oct were used at the outputs of the analogue modulator.

Three listeners served as subjects in the experiment; two music students aged 22 and 24 with audiologically normal ears, and one listener without musical education aged 44, with a unilateral selective permanent hearing loss of about 40 dB at 4 kHz, i.e. outside the frequency region investigated.

All listeners had great experience in the psycho-acoustical measurements. One music student has been selected from a large group of candidates as highest scoring in the *DL* for frequency test.

3. Results

For each of the six masker frequencies applied in the experiment ($f_M = 980$, 990, 995, 1005, 1010, 1020 Hz), five or six appropriate values of masker sensation level L_M were chosen. For each of these L_M values, 60 judgments from a single listener were taken.

These data were used for the determination of the psychometric functions given in Fig. 2. From these functions critical values of L_M were found, corresponding to the threshold detection of the maskee pulse. Threshold detection, i.e. critical values of L_M, correspond to the situation in which the maskee was detected in 75% of the presentations, i.e. in between 100% (no errors) and 50% (guess only). Each of the psychometric functions is determined by 5 to 6 points, that is by 300 to 360 judgments. This number of judgments refers also to each of the points in the tuning curves thus determined. Each of the three tuning curves is then determined by 1800 to 2160 judgments.

L_M values corresponding to the threshold detection of the maskee pulses are presented in Fig. 3 for each of the listeners separately. The horizontal axis refers to the masker frequency f_M. This pattern of presentation was first proposed by SMALL [15], and then used by ZWICKER [21] for direct masking data under the name *psychoacoustical tuning curves*.

4. Discussion

In the psycho-acoustical tuning curves presented in Fig. 3, the top parts, i.e. parts adjoining the frequency of the maskee (1 kHz) are missing. In that region the measurements are particularly difficult. However, the portions of the tuning curves determined are sufficient to make some observations pertaining to the selectivity of the respective influence of the stimuli in the poststimulatory masking near the threshold level (15 dB *SL*).

A particularly significant factor in tuning curves, which makes comparison with data from other authors possible, is the slope or steepness of the curves in the proximity of the maskee frequency. Numerical values of the slopes obtained in this experiment are given in Table 1.

At frequencies, in the range from 5 to 10 Hz above the maskee frequency, the steepness of tuning curves is comparable for all listeners and amounts to between 1 and 2 dB for 1 Hz frequency deviation.

A frequency change of 0,5 Hz, which for very low sensation levels is equal to the difference limen for frequency [12], leads to a change of the masker level by 0.5 to 1 dB, i.e. a change corresponding to the value of the difference limen for loudness. This convergence does not seem to be just accidental and it can possibly support the hypothesis of MAIWALD [9]. Accordng to MAIWALD, the detection of both amplitude and frequency changes within the organ of Corti can be assigned to the same and only receptors which are sensitive

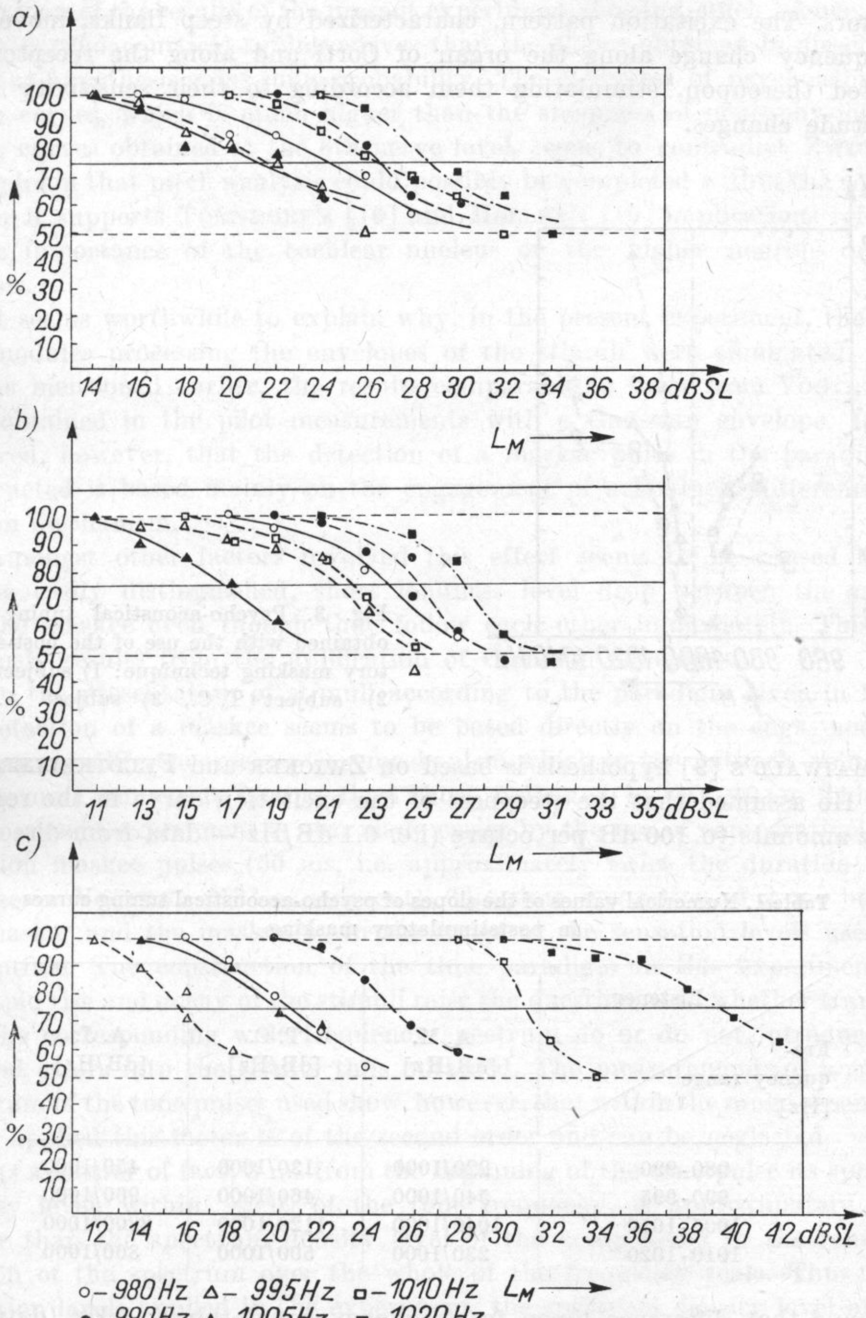

Fig. 2. Percentage of correct responses vs. masking signal level: a) subject A. M., b) subject T. C., c) subject A. J.

to the amplitude variations and operate on the principle of frequency discriminators. The excitation pattern, characterized by steep flanks, moves with a frequency change along the organ of Corti and along the receptors distributed thereupon, stimulating them according to their sensitivity to the amplitude changes.

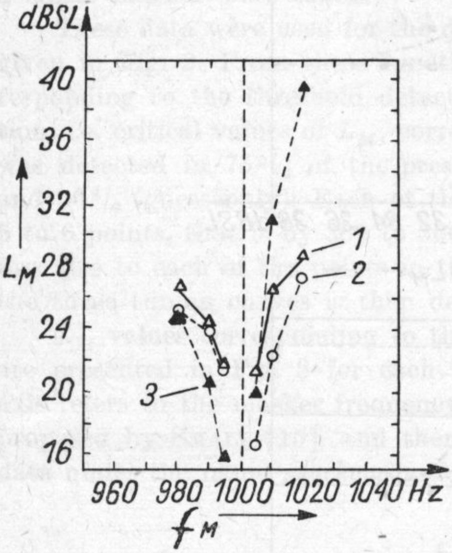

Fig. 3. Psycho-acoustical tuning curves obtained with the use of the post-stimulatory masking technique: 1) subject A. M., 2) subject T. C., 3) subject A. J.

MAIWALD'S [9] hypothesis is based on ZWICKER and FELDTKELLER's [20] data. He assumed that the steepness of the excitation curve in the region of 1 kHz amounts to 100 dB per octave (i.e. 0.1 dB/Hz – data from direct mas-

Table 1. Numerical values of the slopes of psycho-accoustical tuning curves in poststimulatory masking

Listener / Frequency range [Hz]	A. M. [dB/Hz]	T. C. [dB/Hz]	A. J. [dB/Hz]
980-990	220/1000	130/1000	450/1000
990-995	540/1000	460/1000	960/1000
1005-1010	1040/1000	1120/1000	2200/1000
1010-1020	230/1000	500/1000	860/1000

king) and that difference limen for frequency equals about 7 Hz (data from frequency modulation measurements).

With the new experimental data showing that ZWICKER and FELDTKELLER's *DL* for frequency is at least an order of magnitude higher than the actual differential pitch threshold, MAIWALD's hypothesis could not be accepted.

In view of the results of the present experiment showing much higher slopes of the psychoacoustical tuning curves than the slopes obtained in direct masking, the hypothesis gains some probability. The steepness of psychoacoustical tuning curves, which is much higher than the steepness of neurophysiological tuning curves obtained at the 8th nerve level, seems to contradict ZWICKER's [21] opinion that pitch analysis could possibly be completed within the cochlea. Rather it supports TONNDORF's [16] and MØLLER's [10] implications referring to the importance of the cochlear nucleus or the higher neurons in this analysis.

It seems worthwhile to explain why, in the present experiment, the function modules processing the envelopes of the stimuli were eliminated.

As mentioned earlier, the results comparable to those from VOGTEN [18] were obtained in the pilot measurements with a Gaussian envelope. It was observed, however, that the detection of a maskee pulse in the paradigm so constructed is based mainly on the engagement of a loudness difference perception mechanism.

Amongst other factors involved this effect seems to be caused largely by the easily distinguished, short loudness level drop between the masker and the maskee even though they follow each other immediately. This drop obviously results from the application of Gaussian envelopes.

In the presentation of stimuli according to the paradigm given in Fig. 1, the detection of a maskee seems to be based directly on the engagement of a frequency difference perception mechanism which in the author's opinion involves more numerous factors than those indicated by MAIWALD. This task in the present experiment is also made easier by the use of comparatively long duration maskee pulses (50 ms, i.e. approximately twice the duration of the maskee in VOGTEN's [18] experiment). The time separation of 2 ms between the masker and the maskee is, in the range of the sensation levels used, imperceptible. The construction of the time paradigm in this experiment and the rapid rise and decay of the stimuli raise the question as to whether transients and the corresponding wide frequency spectrum do or do not introduce substantial errors into the results thus obtained. The measurements of a running spectrum of the tone pulses used show, however, that within the range of sensation levels applied this factor is of the second order and can be neglected.

As a matter of fact, 3 ms from the beginning of the tone pulse its spectrum density level, within $\pm 5\,\%$ of the tone frequency, is approximately 20 dB higher than the spectrum density level of the components in the remaining portion of the spectrum over the whole of the frequency scale. Thus at the sensation levels applied in the experiment, the spectrum density level of these side portions of the spectrum is almost below the threshold. This results in an almost undisturbed perception of those portions of the stimuli which determine their pitch.

The value of the information contained in this report is partly limited by the fact that stimuli were presented in succession and at low sensation levels only.

However, the data obtained here, together with those of VOGTEN, show that the selectivity of hearing organ as determined by the present psychoacoustical methods (poststimulatory masking) exceeds markedly the selectivity revealed in neurophysiological experiments. It may look astonishing and the more so that some ten years ago the relation between the results of psychoacoustic experiments (simultaneous masking) and neurophysiological findings was exactly opposite.

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