N.A. Dubrovsky, M.N. Sukhoruchenko

SHIFT OF AUDIBILITY THRESHOLDS FOR PURE TONE AT PRESENCE OF PULSE MASKER IN THE BOTTLENOSE DOLPHIN

Andreyev Acoustics Institute
No. 4, Shvernika Ul, 117036 Moscow Russia
Ph.: (095) 126-7401; Fax: (095) 126-8411
E-mail: dubrov@akin.ru

Effect of pulse masker on audibility of the pure tone was investigated in the bottlenose dolphin (Tursiops truncatus). The masker represented a sequence of short pulse pairs with an interpulse interval in pair 50 ms and with pairs repetition rate 300/sec. Thresholds of audibility of test tone in frequency band 20 -100 kHz are measured at presence and at absence of the masker. Conditional-reflex method was used with food as reinforcement. Dependence of the threshold shifts (TS) on frequency of a test signal has the complex form. This dependence can be presented as a superposition of three components: (1) an oscillating component of TS curve replicating oscillations of the masker spectral density (result of the profile analysis of the pulse masker); (2) a component falling monotonously with growth of frequency up to 80 kHz, which is very distinctive from a component arising at action of white noise; (3) a high level component independent on frequency. The following auditory features seem to relate to the above components. A component (1) represents a timbre of the pulse masker; a component (2), relates presumably to pitch corresponding to frequency 1/t. A component (3) shows auditory feature of the random noise, which is not connected with periodic oscillations of spectral density of the masker.

The echo from an underwater target caused by a single ongoing pulse of the dolphin represents frequently a sequence of several pulses with short interpulse intervals. In accord to results of electrophysiological study of the bottlenose dolphin brain [Popov, Supin, 1986], the minimal interpulse interval, at which the evoked nervous response to the second pulse (equal in amplitude with a first one) can be still detected amounts to 200-300 μs. Nevertheless, the dolphin well discriminates pairs of pulses at duration of interpulse interval essentially smaller 200-300 μs [Vel'min, Dubrovsky, 1975; Bel'kovich, Dubrovsky, 1976]. The ability to discriminate pulse pairs at so small intervals compels to draw attention to a mechanism of the spectral analysis for an explanation of such discrimination.

Spectral density of a pulse pair can be represented by a periodic function with maximums at n/t (n=0, 1, 2, 3..., t - time delay in a pair). Thus, a. pair of pulses has an oscillating spectral density with the period f=1/t. The distribution of neural excitation level over different auditory filters can be considered as the "auditory spectrum" of physical stimulus. The thresholds of masking of tones by pulse pairs can serve as sensitive test for research of "auditory spectrum" of a simulating echo signals The method of research of thresholds of masking of pure tones by complex stimulus has received in the literature the name "of the profile analysis the "auditory spectrum" of pairs of pulses represents the large interest for the researcher of mechanisms of the analysis of echolocation signals in the acoustical system of the dolphin.

In the present work the influence of pairs pulses on detection of pure (test) tones was investigated on bottlenose dolphin. The thresholds of test tones detection were measured both at presence of a pulse masker and in its absence. The work was implemented in a concrete pool. A dividing net 2 m in length was fastened by one end of an experimental footbridge. The starting position of an animal was developed on distant from footbridge end of the net. Acoustic radiators were suspended 1 m from a footbridge on the both sides of the net at 1,5 m depth. Both radiators created the same masker simultaneously. Any radiator could emit the test tone randomly. At occurrence of a test signal the dolphin left starting position and approached to the radiator, from which a test signal appeared. For the correct response the dolphin was encouraged with a fish. The test signal was switched off after the dolphin approached a radiator. Food compensation or its absence in case of mistake served as a signal for the dolphin to return to a starting position.

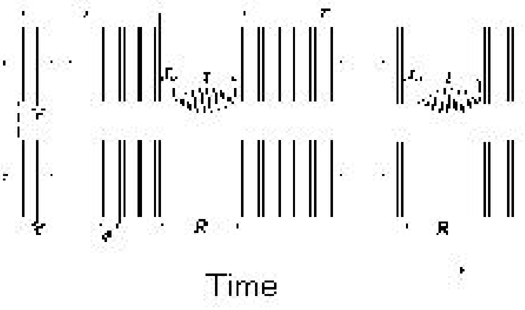

Fig. 1.

The time diagram for acoustic stimulation is shown in Fig. 1. A masker was interrupted once a second, and in a pause R (duration 7 ms) with a delay r, on one of radiator appeared a test signal, which was a short burst of pure tone with duration t = 6 ms, including forward and back fronts 1 ms each. Pairs of pulses constituting a masker had the fixed interpulse interval t= 50 μs and their repetition rate was equal $1/f$ -300/sec. The period of a pulse masker T had duration about one second. Acoustic pulses were created by shock excitation of 10 mm piezoceramic spheres by short video pulses. The acoustic pulse was registered at the end of a dividing net, at rostrum of an animal in its starting position.

The peak values of pulses were constant and corresponded approximately 60 dB above a threshold of audibility of a single pulse. The duration of a single acoustic pulse in water did not exceed 30 μs. Frequencies of the test tone were taken with a step 10 kHz, equal to a half-period of spectral density oscillation of a masker, and so that these frequencies took place on extremes of a spectrum of a masker. The test tones arose also ones per second at absence of a masker.

The thresholds were determined by a staircase method, which allows automatically supporting a level of a signal in a threshold zone. The amplitude of a signal was gradually lowered from obviously above threshold to a level, at which dolphin made the first mistake, then amplitude raised, till dolphin again made incorrect answer. Then amplitude lowered down again until the dolphin made a mistake, etc. The number of such reversals at determination of a threshold reached 10 in presence of a masker and 5 – 6 in absence of a masker. Change of signal amplitude in a threshold zone was made with a constant step 5 dB. The total number of presentations of test stimulus in a threshold zone at each test frequency was varied from 20 to 30. Threshold value in the given series was estimated by averaging of interim values of the signal amplitude between ones related to correct and wrong answers in points of reversals. The number of repeated sessions at each frequency in presence the masker was 4 - 5, in its absence - 2 - 3. Repeated threshold values also were averaged. The thresholds presented in decibels relative to some arbitrary chosen amplitude of a test signal at input of radiator.

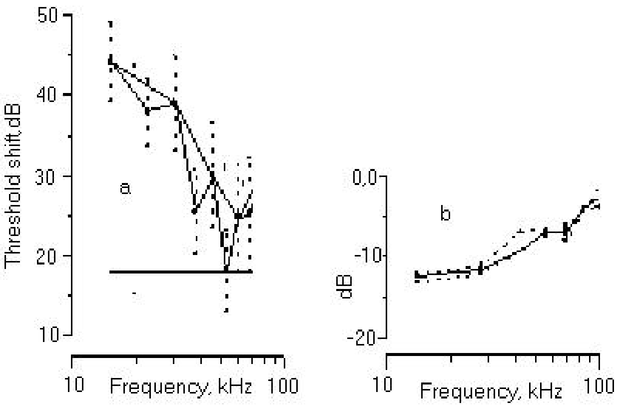

Fig. 2.

Fig. 2a illustrates dependence on frequency the threshold shift (TS) caused by masking. The vertical bars show estimations of a standard deviation of difference in average TS values gained in absence and in presence of the masker. The dependence TS from frequency has rather complex form and can be submitted, as the superposition of several curves. Oscillations of the TS curve are very pronounced. Extremes of spectral density of a masker are shown by arrows aver each extreme. The arrows directed upwards, correspond to maxima of spectral density of a masker, directed downwards - to minima. It is obvious that oscillations of the TS curve correlate with extremes of spectral density of a masker up to 80 kHz. The peaks of the TS curve relate precisely to maximum of masker spectral density and holes of TS curve to minima. However that correlation is not observed any more by frequencies higher than 80 kHz

The Fig. 2a shows also decline of the TS curve as a whole with growth of frequency of a test signal up to 70 kHz. Having connected all peak values of the TS curve (Fig. 2a), we shall get a broken line, which shows, that the monotonous fall of TS occurs with different rate on sites 1-2 and passes in rise on a site 3 at frequencies above 70 kHz. A spectrogram of a single acoustic pulse is given in fig. 2b. The spectrogram can be considered as an envelope of spectral density curve of a pulse pair. The mutually opposite dependences of spectral density of a single pulse and of broken line in Fig. 2a on frequency are observed. While spectral density of a single pulse grows with frequency, the TS on a broken line fall up to frequency 80 kHz, and only within frequencies 80-100 kHz both rise TS, and growth of spectral density of a single pulse are observed.

Let's draw also straight line parallel to an abscissa through the lowermost point on the TS curve. The straight-line shows that TS level, to which TS decreases, is still high enough (almost by 20 dB exceeds a threshold of audibility at 70 kHz in absence of a masker). Let's admit that this line represents an independent on frequency component of cumulative effect caused by a masker.

Let's consider physiological sense of the selected different components of the TS curve. The correlation of peaks of the TS curve with extremes of a spectrum of pair pulses is not unexpected. Psychoacoustical research of masking of pure tones by stimulus with various complex spectra, for example, noise with rippled or oscillates a spectrum or by speech sounds find out the similar phenomenon. It is obvious, that the peaks of the curve of TS represent " an hearing spectrum " pairs of pulses. Though on the frequencies higher 80 kHz correlation is not found out, its absence can be explained by imposing of an ascending branch of a broken line (fig. 2a, component 3).

Thus, the results of the profile analysis allow explaining shifts of thresholds caused by a pulse masker. Unexpected the monotonous fall of TS with frequency (fig. 2a, components 1-2 broken lines) is represented. In - first, as was already spoken, monotonous component of TS and spectrogram of a single pulse are in mutually of return dependence on frequency (fig. 2a and 2b). In - second, the important difference frequency dependences of the TS curve on frequencies 20 -70 kHz (components 1-2 broken lines) and curve of masking of pure tones by white noise is observed. It is known [Zwicker, Feldtkeller, 1971], that at the people the masking by white noise on frequencies higher 500 Hz grows with speed 10 dB for one decade. This growth is clear in connection with expansion of critical bands with increasing of frequency. The similar dependence of masking is received by white noise from frequency and on bottlenose dolphin [Johnson, 1968]. Submitted on a fig. 2a the broken line shows TS fall almost on 20 dB at increase of frequency of a test signal from 20 up to 70 kHz. To explain by usual spectral mechanisms such behaviour of the TS curve it is not successful. Only on frequencies 70 - 100 kHz the small increase of TS with frequency (fig. 2a, component 3 of broken lines) is observed, as it takes place at masking by white noise (and according to the form of spectral density of a separate pulse, fig. 2b).

The Fig. 2a shows, that the most significant shift of a threshold falls at frequency of a test signal 20 kHz, i.e. at frequency $f_0=1/t$ (t = 50 μs). It suggests an idea that the unusual dependence the TS curve on frequency results from unusual masking of a simple (one frequency) tone by a complex tone. Contrary to a simple tone, periodic (comprised of a set of harmonics) signal with oscillatory spectral density is named frequently by complex tone. It is possible for complex tone with sufficient accuracy to pick up a pure tone, which pitch coincides with a fundamental frequency of a periodic signal or with frequency $f_0=1/t$ for pair of pulses or for noise with rippled spectral density. Such noise is produced by superposition of a burst of white noise with its delayed replica. Frequency $f_0=1/t$ is named often also as fundamental frequency of aperiodic broadband signal.

Human perception of a pitch of pulse pair even at missing fundamental frequency $f_0=1/t$ in the spectrum had been studied a long ago. Pitch of a complex tone is called frequently virtual one in the literature, as the amplitude spectral component at frequency $f_0=1/t$ can be rather small or not be detected at all on a background of other spectral components. The ability to respond to the fundamental frequency of complex periodic sounds with missing fundamental frequency was shown for all investigated vertebrates - fishes, frogs, singing birds, cats, Mongolian gerbils, monkeys [Henry, 1997]. The ability of dolphins to discriminate noise with rippled and uniform spectral density has been investigated in detail [Au, Pawloski, 1989]. Widely distributed among vertebrates ability to find out time – spectral periodicity of complex stimulus testifies to importance of auditory feature caused by such periodicity. Only pitch can be this feature. There is no basis to deny initially the dolphin ability to perceive a tonal colouring of complex stimulus with a periodic spectrum. The opportunity of an explanation the unique echolocating abilities of dolphins by sensation of pitch of complex stimulus (coherent sequence of pulses) has been discussed in the literature for a long time [Au and Hammer, 1980; the review in: Moore et al, 1984].

It is no doubt, that the dolphin perceived a pitch of a masker in our experiments. As spectrogram of a single pulse composing a pair reveals rather strong fall to frequency 20 kHz (fig. 4b), it is impossible to explain increase of a threshold by 30 dB at test frequency 20 kHz (fig. 4a) simply by masking of tone by tone of the same frequency. Spectral interval $f_0=1/\tau$ between peaks of a spectrum of our masker was also equal to 20 kHz. Therefore so strong shift of a threshold at frequency 20 kHz can be connected only with significant "strength of pitch" of complex tone (masker). The term "strength of pitch" of a complex sound is used in psychoacoustics for a long time and till now it is important characteristic of complex tone perception [Wiegrebe, 2001].

It is much more difficult to explain the fall of TS with frequency (fig. 2a). Let's assume, that "strength of pitch" of complex tone is determined by number of spectral peaks resolved by critical bands, but also and by accuracy of the analysis of the period of spectral density on a scale of "auditory" frequencies. In the present experiments the number of spectral peaks of a masker was fixed (in all experiments a delay in pair had the same value - 50 μs). The accuracy of the "auditory" analysis of the spectral density period on the auditory frequencies scale is changed. The accuracy of the auditory analysis of spectral density falls with frequency. The period of spectral density is reproduced in the auditory system by change of a level of a signal at outputs of the neighbouring critical bands. Owing to broadening of a critical bands with frequency, the lesser number of critical bands is due for each following more high-frequency period of a spectrum. Thus the accuracy of an estimation of the period of spectral density becomes more and more rough. The roughest estimation should be in the range of frequencies, on which the neighbouring auditory filters resolve only neighbouring extremes of a masker spectrum. At the further expansion of critical bands, even the peak values of spectral density are not resolved any more. Period of a masker spectrum at frequency 20 kHz contains approximately 10 critical bands (if relative width of a critical band is about 10 %). The period contains only two critical bands at frequency 100 kHz. Therefore a limit in resolving peaks of a spectrum is already achieved near frequency 100 kHz.

If the accuracy of the analysis determines "strength of pitch", at the expense of this mechanism the different areas of a spectrum can play a different role in forming the pitch of complex stimulus. The higher frequency of auditory filter the lesser importance it has for forming of "the pitch strength" Accordingly this filter has smaller masking effect of complex tone (of our masker). Easing of masking effect on pitch of a masker takes place with growth of frequency of test tone and, as a consequence, falling down the TS curve.

Thus, we explain the monotonous decrease of TS with frequency of test tone by fall of accuracy of the spectral analysis in frequency band around of test tone. This fall is connected with contribution of local area of a spectrum in forming of "strength of pitch". That fact, that the different areas of a spectrum play a different role in perception of pitch of complex stimulus, is shown in psychoacoustical experiments on the filtered noise with rippled spectrum [Warren and Bashford, 1988; Yost and Hill, 1978]. Ability of the cat to distinguish complexes of harmonics based on the fundamental frequency (300-400 Hz), i.e. on pitch of a complex, is shown in behavioural experiments [Heffner, Whitfield, 1976]. The quantitative characteristic of sensitivity the cat to distinction of the fundamental frequency of complexes, used by the authors, testifies about monotonous fall of sensitivity when the central frequency of a complex increases. The authors [Heffner, Whitfield, 1976] explain such dependence by fall "strength of pitch" of a complex.

There is the third TS component, shown separately on fig 2à as a horizontal line. On the data of psychoacoustical research, the human at listening noise with rippled spectral density perceives two different attributes of stimulus: noise and tonal (Patterson, et all, 1996). Independent of frequency component of the TS curve (fig. 2a) emphasizes high level (about 20 dB) of random noise component, which has not been connected to periodicity of spectral density of pair of pulses.

Thus, the action of pulse masker on thresholds of audibility of pure tones by bottlenose dolphin finds out complex character of this effect. It is possible to select three different components of the TS curve. First part, which reflects exact correlation of oscillations of the TS curve and extremes of a spectrum of a masker along frequency scale. Such correlation represents result of the profile analysis ("an internal auditory spectrum") of masker. "The auditory spectrum" of masker provides, we believe, timbre quality of a masker. Opposite to masking by white noise, the shift of a threshold caused by pulse masker monotonously falls with growth of frequency of test tone. The maximum of a monotonous component of the TS curve coincide with test frequency $1/\tau$, equal 20 kHz. The monotonous component of the TS curve is related to pitch of a pulse masker. The monotonous decrease of TS with growth of frequency of test tone is explained by decrease with frequency of accuracy of spectral analysis in area around the test frequency and reduction of the contribution of a local fragment of a spectrum in general "strength of pitch".

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